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California Agriculture

Restoring clarity:
The search for Tahoe solutions

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News departments

Cover: During the last half century, Lake Tahoe has lost 30% of its famed clarity. Scientists report new findings on the major culprits — sediments and excess nutrients. An editorial overview reviews the lake's history, and news stories explore clarity models, Sagehen reserve and weed control. Shown: Emerald Bay.

Research articles

. . . more research articles

Letters

WHAT DO YOU THINK?

The editorial staff of *California Agriculture* welcomes your letters, comments and suggestions. Please write to us at calag@ucop.edu or 1111 Franklin St., 6th floor, Oakland, CA 94607. Include your full name and address. Letters may be edited for space and clarity.

The politics of market incentives

At the end of his interesting article ("Market incentives could bring U.S. agriculture and nutrition policies into accord," January-March 2006), Josh Miner asks about making targeted cuts in a commodity support program to free more resources for the food stamp program.

The agribusiness lobbyists who purchased the relevant political influence to get those programs and funding in place are not going to easily acquiesce to their reduction. No governmental budget is an equal playing field where only the most worthy projects are funded.

Food stamp recipients are not likely to have money for campaign contributions, and they are not well organized into a block of committed voters on this issue. Since their numbers tend to be in urban areas, their representatives often prefer to be on committees that deal with urban issues. The way forward for Miner's proposal would be to get the food stamp program and other related programs moved into federal health, education and welfare departments or into housing and urban development departments, where the voices of the poor are heard most clearly. Agricultural committees represent farmers and the interests of rural states that grow the food, not the people who mainly eat it.

Complicating the problem is the current trend to cut back farm subsidies in general as a part of free trade, and use world trade as a method to assist developing countries. The funds that Miner wants to use may shortly no longer exist.

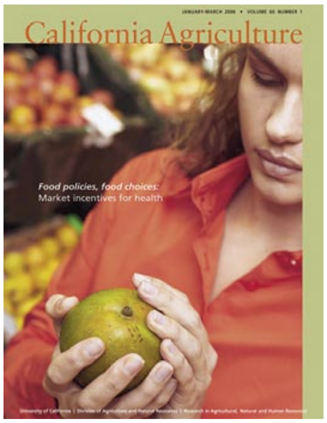
Bruce Bibee
Rosemead, Calif.

Josh Miner responds:

Bruce Bibee's point about the political (un)feasibility of cutting or redirecting commodity support payments might seem intuitive, but is more appropriate to a discussion of the political climate surrounding the 2002 Farm Bill. Currently in

— continued on page 44

Washington there exists powerful, bipartisan support for at least capping direct payments, led by ag-friendly Senators Chuck Grassley (R-IA) and Byron Dorgan (D-ND), as well as President Bush. This, coupled with widespread public sentiment against direct agricultural subsidies and the likelihood that such payments will soon be deemed in violation of international trade agreements, makes the debate leading up to the 2007 Farm Bill a perfect time to discuss creative ways to redirect all or part of those payments.



The January-March 2006 issue

While Bibee's assertion that that food stamp advocates have to date not been instrumental in setting national farm policy is true, describing them as being "not well organized" or lacking in political access is inaccurate. They simply focus on the wrong issue: ending hunger (a problem affecting perhaps 10 million Americans) instead of promoting healthy diets, which between 50 and 210 million Americans could have benefited from in 2000. Were food stamp advocates to begin lobbying for a U.S. food and farm policy rooted in health promotion and equal access to affordable, healthful foods among low-income consumers, as opposed to continuing their single-minded focus on ending hunger, they would no doubt become one of the most powerful constituencies influencing the 2007 Farm Bill debate.

Tell us why you read *California Agriculture*, and what you would you like to see in these pages in the future.

Go to http://californiaagriculture.ucop.edu, or write calag@ucop.edu

Readers share their interests

Editor's note: In our last issue, we announced a brief survey of reader interests. Several reader responses follow.

I am a 56-year-old disabled Vietnam vet. I have a B.S. in soil science and half the work done on an M.S. in natural resource conservation and environmental planning. I have done field labor, including harvesting wine grapes and picking tree fruit. This issue's article on grape pickers' back injuries rang true ("Smaller loads reduce risk of back injuries during wine grape harvest," January-March 2006). The same hold true for warehouse construction, which I have done.

I am interested in sustainable agriculture, nonconventional/nontraditional agriculture and water issues. I consider myself a conservationist: manage and use resources wisely instead of the waste and mismanagement that currently prevails.

What I do not like to read in *California Agriculture*: articles that get bogged down in statistical analysis, probabilities and standard deviations. I realize it is necessary to prove or back up the research data, but it is a big turnoff. Also, I do not like articles that do not have a glossary or define research/subject-specific terms.

What I want to read: articles on sustainable agriculture, conservation, water issues and other types of agriculture than the current conventional (i.e., chemical/pesticide) methods. I would like to see more articles on research facilities, plus articles geared to consumers.

Dennis Bell
Redlands, Calif.

I like to learn about innovative scientific discoveries made by UC researchers that make California agriculture more efficient.

In your January-March 2006 issue, I particularly liked the Outlook discussion on the 2007 Farm Bill. You do not find this type of conversation in the regular media. I encourage you to do follow-ups on how the major issues are resolved, and why the decisions were made.

One of America's major potential problems is the giant increase in the number of overweight/obese citizens. Josh Miner's thought-provoking proposal to use money from the commodity support funds to create price-lowering incentives has great merit. It is obvious that America must change its eating habits.

Finally, *California Agriculture* used to feature quality stories on youth and the community. I suggest that you restart coverage of California's 4-H program. Telling how the UC DANR/4-H system is helping California youth grow into responsible citizens would be powerful.

Don MacNeil

Conveyor belts for grape harvest

After reading of all the problems picking grapes ("Smaller loads reduce risk of back injuries during wine grape harvest," January-March 2006), I picture a traveling gondola car with three belt conveyors attached. This would eliminate all of the tubs and half of the pickers. The grapes would be placed directly on the conveyor belt and end up in the gondola.

James Demin
Glendora, Calif.


Smaller tubs reduced rates of harvesters' back symptoms.

Editorial overview

Photos: John Stumbos

Science a decisive factor in restoring Tahoe clarity

Western settlers first discovered Lake Tahoe in 1844, when General John Fremont and his tired group of cavalry gazed upon its cobalt waters from a mountaintop to the southwest. For the next century, stagecoaches brought steadily increasing summer visitors. When Mark Twain first saw Tahoe he was so impressed by its blue waters that he described it as the "fairest picture the whole earth affords."

The 1857 discovery of gold and silver in the Comstock Lode at Virginia City created the first major disturbance of the Lake Tahoe Basin. Loggers clear-cut most of the basin's timber to shore up the mines of the Comstock; when the mines ran out of silver most of the old-growth timber was also gone.

Charles R. Goldman
Director
Tahoe Research Group
UC Davis

White fir and brush grew back in dense, overcrowded stands, which in recent years have created a major fire hazard. This revegetation was important, however, in slowing the high soil-erosion rates that characterized the peak logging period. The high losses of soil, chronicled in lake sediments, dropped back to less than one-quarter of those that occurred during the lumbering activity.

Lakes are reservoirs of history. Their bottom sediments are an indelible record of what has occurred on land, air and water. The sediments of the Tahoe Basin are thought to contain a continuous 1-million-year record of climate, one of the longest on the continent. Fossil remains of invertebrates and fish scales portray the postglacial history of Lake Tahoe, beginning about 11,000 years ago. More recent sediment layers preserve sawdust from the Glenbrook sawmills of the Gold Rush, chronicle the introduction of tetra ethyl lead in gasoline in 1948, and record the appearance of mercury from industrial atmospheric pollution.

When the Comstock mining ended, forests and brush cover returned to the basin within about 20 years, and with it Tahoe recovered its pristine quality as one of the clearest large lakes in the world. In 1887, John Le Conte measured the lake's transparency at over 100 feet, a revelation that provides hope that the lake can once again recover from the recent period of high development activity.

At top: **Winter, spring, summer and fall in the Lake Tahoe Basin.**

Over 70% of the Tahoe Basin is U.S. Forest Service land under the control of the federal government. After World War II, developers built roads and structures using flatland technology unsuited to the steep slopes, fragile soils and limited vegetation cover of this subalpine area. In the late 1950s, when the value of wetlands was not well understood, approval was given for Dillingham Corporation to develop a marina on Pope Marsh, the single largest wetland in the Sierra Nevada. This became the extensive Tahoe Keys at the south end of the lake, and the important filtering capacity of Pope Marsh was lost forever. To make things worse, the major tributary to the lake, the upper Truckee River, was relocated along the east side of the Tahoe Keys and now delivers nutrients and sediment directly to the lake without the filtering benefits of the former wetland. (Scientists have proposed that it be diverted into the narrow remaining marsh known as Cove East.)

Tahoe Keys contains warmer water than that of the lake, and it has provided habitat for a number of invasive plants and animals. These invasive species, now exemplified by the spread of the notorious waterweed Eurasian watermilfoil, have gradually moved from the Keys to other areas around the lake. Warm-water and aquarium fish introduced to the Keys have moved to the new, warmer microenvironments that the waterweeds have created. Other invasive fish, particularly the cold-water-tolerant smallmouth bass, may eventually threaten the very existence of the native minnow, trout and kokanee salmon populations. The invasion of these exotic organisms will be further aided by the gradual warming of the lake. Tahoe's enormous volume of 39 trillion gal-

Editorial overview

Phil Schermeister

The Tahoe Keys development on the lake's south shore destroyed Pope Marsh and put part of the Truckee River into a canal, so that it now delivers nutrients and sediment directly to the lake without the filtering benefits of the former wetland.

lons (156 cubic kilometers) of water has already warmed nearly a full degree Fahrenheit over the last 30 years.

With the construction of casinos at the state line on the north and south ends of the lake and the development of a summer boating and winter ski industry, Tahoe gradually attained the status of a resort destination. The lake is so popular in the summer that it is not unusual to record a million vehicle miles around the lake in a single day. The selection of Tahoe for the 1960 Winter Olympics gave it global publicity and greatly increased the visitor traffic. The beauty of this lake is now world-renowned, but human impacts have gradually taken their toll.

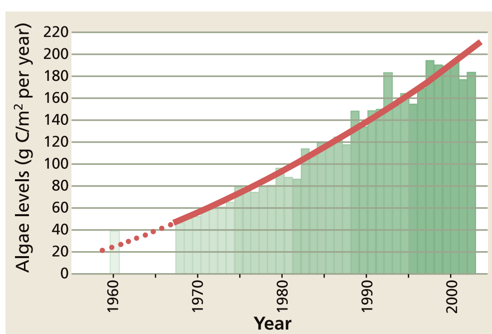
Since my lake clarity and algal productivity studies began in 1959, the lake has lost a third of its remarkable transparency, and algal growth has increased by about 5% per year (see figures below and on page 50). Small particles of dust and sediment remain suspended in the water column for years, adding to the gradual but relentless transparency loss. Air pollution is also a factor; nitrogen pollution of the lake is greater from the atmospheric deposition than it is from stream-water input.

This limnological research (which examined the physical, chemical and biological features of the lake) convinced civil and environmental engineers to require the total export of treated and untreated sewage from the Tahoe Basin. Although the availability of a basinwide sewage system probably stimulated additional near-shore development, this export was a major and necessary step in preserving water quality. The success of sewage diversion strengthened the realization that keeping Tahoe blue was difficult, but achievable. Also instrumental in building public awareness were articles in the journal *Cry California* and the growing influence of the League to Save Lake Tahoe, which translated the scientific data collected by the UC Tahoe Research Group into lay terms. As the league's membership grew, so too did an understanding of the growing threats to Lake Tahoe's water quality. "Keep Tahoe Blue" bumper stickers began to appear across California and Nevada.

Several landmark decisions have been made since my arrival at Lake Tahoe in 1958. Creation of the Tahoe Regional Planning Agency, for example, brought a single central authority to a lake divided by two states, five different counties, and various municipalities, agencies and local governments. This federal mandate was unpopular in some circles, since it imposed federal control on two states. However, it provided essential coordination of efforts to regulate future development and repair the damage that had already been done. Another historic decision came in 1984, when U.S. District Judge Edward Garcia halted development in the basin for 2 years until control measures could be established to protect the resource. Strong, science-based evidence has been the decisive factor in successfully defending the Tahoe Regional Planning Agency from legal assaults over the years.

In 1997, at the invitation of current U.S. Senate minority leader Harry Reid (D-Nev.), President Bill Clinton and Vice President Al Gore attended the first Lake Tahoe Summit, a unique environmental event that gained worldwide attention. The Tahoe Summit is now held annually, and Reid and U.S. Senator Dianne Feinstein (D-Calif.) have continued to champion protection of the lake. This fall the UC Davis Tahoe Environmental Research Center will move into a new world-class facility that will greatly expand research, education and science-based decision-making for the Tahoe Basin.

After more than a century and a half of development and disruption since Western settlers first discovered Tahoe, the lake remains extraordinarily beautiful and remarkably clear. It is one of the West's most treasured resources. We have now moved beyond most of the conflicts of the past. Developers and conservationists generally agree that everyone loses if Tahoe's water quality and scenic beauty are allowed to deteriorate. New scientific discoveries on lake temperature and nutrients, and watershed ecology, together with developments in monitoring and adaptive management, give further promise for the future of the lake. There is growing public understanding of the value of this unique natural resource and increasing willingness to do whatever is necessary to protect Tahoe for this and future generations.



Algae levels have increased steadily since the 1970s, contributing to Lake Tahoe's loss of clarity. The lake's temperature is also increasing, which could allow the growth of different kinds of algae that further muddy the water.

UC's Sagehen reserve is California's newest experimental forest

Last November, the USDA Forest Service announced the designation of the 8,100-acre Sagehen Creek Watershed as an experimental forest. The announcement, made jointly with UC Berkeley, establishes Sagehen — located 8 miles north of Truckee — as the first new experimental forest in California in more than 40 years.

"Experimental forests have played a major role in improving the management of forest resources throughout the country," says Alex Glazer, director of the UC Natural Reserve System, which oversees Sagehen and 34 other UC-operated research reserves throughout California. "This collaborative research program brings together managers and scientists with distinctive viewpoints and skills, but the common goal of achieving important, practical outcomes."

The UC Natural Reserve System encompasses approximately 130,000 acres of protected natural land, which is available for university-level instruction, research and public outreach. The forest will be managed by the Tahoe National Forest, UC Berkeley and the Pacific Southwest Research Station.

Pioneering field research

UC Berkeley's Sagehen Creek Field Station, located on 452 acres within the Tahoe Basin, has been a center for pioneering field research for more than 50 years. In 1951, UC Berkeley professors A. Starker Leopold and Paul Needham first obtained permission from the Forest Service to establish a High Sierra facility for wildlife and fisheries studies.

Over the ensuing years, the professors and their graduate students literally built the station from the ground up. Each summer they would add new structures — laboratories, cabins, meeting rooms, a cookhouse — gradually creating a year-round research center.

Sagehen has proven to be an ideal area for study. Located at 6,380 feet on the eastern slope of the Sierra, the basin's complex topology and hydrology provide a mosaic of vegetation communities, including coniferous forests, montane chaparral, sagebrush steppe, wet and dry meadows, and spring-fed fens.

Initially, Needham and his students focused on fisheries while Leopold and his students studied wildlife, but succeeding generations of UC researchers expanded the focus to include the basin's fens, insects, flora, forests and hydrology.

UC Davis professor Peter Moyle, an expert in fish ecology, works with a team of graduate students at Sagehen Creek Field Station.

Sierra-based studies

Several current projects will have important implications for the ecology of the Tahoe Basin. In one, UC Berkeley professors John Battles and Scott Stephens are heading up a Fuel Management National Pilot Project to evaluate the effectiveness of strategically placed area treatments (SPLATs) in reducing wildfire danger.

In another, UC Davis professor Peter Moyle and colleague Virginia Boucher are leading a study funded by the U.S. Fish and Wildlife Service on the restoration of native Lahontan cuttroat trout, using different strains of fish as well as different techniques for creating sustainable populations. "Sagehen is perfect for our study," Boucher says, "because we have the best baseline data set on fish in the Sierra. It is also right next door to Independence Lake, which has one of the last sustainable wild cutthroat populations."

A team of UC Berkeley researchers led by Inez Fong, with Sagehen faculty reserve manager Jim Kirchner, will focus on developing a deeper understanding of the life cycle of water on Earth. For example, small, automated "chemical laboratories" will be placed beside the streams to send back continuous chemical and isotopic measurements to identify the water's source.

"If we can relate the pattern through time as these chemical fingerprints change," Kirchner ex-

A unique underwater observatory allows scientists to monitor fish activities at Sagehen.

plains, "we will be able to answer questions like whether streamflow during storms is coming from recent rainfall flowing into the stream quickly, or if it's coming from shallow runoff moving down hillsides and into the channel through the subsurface, or whether the new rainfall is pushing out old water from deep in the fissures between the rocks."

Jeff Brown, manager of the station, is confident that Sagehen can play a complementary role to other Tahoe-based research. "Sagehen Creek and Lake Tahoe are both part of the Truckee River watershed," he notes, "yet here researchers can do manipulative studies that often can't be done within the Tahoe Basin itself. Research here will have impact throughout the Sierra and across the country."

— Jerry Booth

For more info:

http://sagehen.ucnrs.org/index.html

http://nrs.ucop.edu/Transect-Sagehen.htm.

Weed control helps prevent erosion into Lake Tahoe

Lake Tahoe is currently the focus of numerous projects aimed at halting further degradation of its famed water clarity and quality, but historically, invasive weeds have received little attention.

Current research suggests that growth of algae in the lake is fueled by inputs of phosphorus associated with sediment runoff. "The expansion of tap-rooted perennial weeds, especially in riparian areas, can accelerate erosion rates," says Wendy West of UC Cooperative Extension in El Dorado County. "Weeds also have a deleterious effect on recreation, aesthetics and habitat." West is co-coordinator of the Lake Tahoe Basin Weed Coordinating Group, a broad, interagency effort that began meeting in January 2002 to identify, map and control invasive weeds.

The Lake Tahoe Basin is a classic example of a region where weed spread pressure is high, due to its bistate border location, historical escaped ornamental populations, and the seasonal influx of tourists, West says. The lake spans two states and five counties, with differing regulations governing pesticide use.

In 1998, after locating a single perennial pepperweed *(Lepidium latifolium)* plant growing on a roadside in Incline Village, the University of Nevada Cooperative Extension (UNCE) mounted a public education campaign to identify and eradicate other populations.

To build bistate support for perennial pepperweed management, a series of meetings was convened that included major land-management agencies, the Tahoe Regional Planning Agency, the Lahontan Regional Water Quality Control Board (LRWQCB), city and county representatives, volunteers and others stakeholders. With approval from LRWQCB and private landowners, chlorsulfuron was applied to infestations away from water by certified pesticide applicators between 1999 and 2001, with excellent results.

By 2001, however, it was clear that perennial pepperweed was not the only invasive weed threatening the Tahoe Basin. At the request of the U.S. Forest Service, the weed-coordinating group was formed in 2002 with a 5-year memorandum of understanding. More than 20 invasive species are currently on its "weeds of concern" list, including yellow starthistle *(Centaurea solstaitialis)*, Eurasian watermilfoil *(Myriophyllum spicatum)* and curly pondweed *(Potamogeton crispus).*

Kim Melody of the Lake Tahoe Basin Weed Coordinating Group (left) provides a resident of the Dollar Point area with alternate landscaping plants to replace invasive Scotch broom removed from her yard.

The group's activities include monitoring, prevention and eradication campaigns, and public outreach and education. For example, in 2005 the group launched a campaign against Scotch broom (*Cytisus scoparius*), which has roots that fail to stabilize soil. Last summer, area residents traded in Scotch broom plants for free replacements of more acceptable noninvasive landscaping plants.

"The best way to eradicate and control weeds is to prevent their introduction and establishment," says Susan Donaldson, UNCE water quality and weed specialist and co-coordinator of the weed group.

— Editors

Models clarify Tahoe clarity loss

Phil Schermeister

Tahoe is one of the most beautiful lakes in the world, with such clear blue water that you could once see to depths of more than 100 feet. But Lake Tahoe's extraordinary clarity has declined for half a century and today you can usually only see to depths of about 70 feet.

While the water has gotten less clear, UC researchers have elucidated one important thing: the causes for the murkiness. Just about anything in the Tahoe Basin from eroded soil to air pollutants can end up in the lake, so restoring its clarity will require basinwide management. To help guide this process, UC Davis researchers have developed a model that accounts for what gets into the lake, where it goes once it's in the lake, and finally how it all affects clarity.

"The model connects land-use and policy decisions to what's actually going on in the lake," says Ted Swift, who worked on the lake clarity model while at UC Davis and is now an environmental scientist at the Department of Water Resources in Sacramento.

Lake Tahoe is so clear because it is very deep and the water that goes into it is very pure. The lake reaches a depth of about 1,650 feet, making it among the 10 deepest worldwide and one of the deepest nationwide, second only to Oregon's Crater Lake, which reaches a depth of about 1,950 feet.

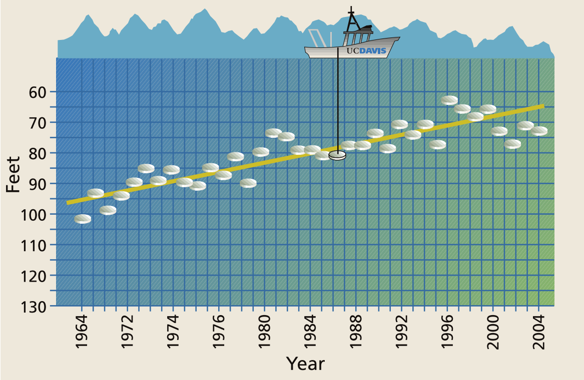
The water that goes into Lake Tahoe is so pure for two reasons, Swift explains. First, much of it falls directly into the lake as rain or snow because the watershed is small relative to the lake's surface area (roughly 300 square miles vs. 200 square miles). Second, the water that drains into the lake has historically been low in nutrients and sediments, Swift says, partly because the watershed is small and partly because it is mostly granite so the soils are relatively sterile.

Why is clarity declining?

"Old-timers say Lake Tahoe is not as clear and blue as it used to be. It's still beautiful but it is gradually getting milkier and greener," Swift says. The research documenting the lake's 30% clarity decline was pioneered by UC Davis limnologist Charles Goldman (see page 45), who in the late 1960s began systematically measuring its Secchi depths. This simple but powerful technique entails lowering an

John Stumbos

Historically, erosion into Lake Tahoe has been low because of the high percentage of granite and granitic soils in the watershed.



Above, **Using the white Secchi disk to measure water transparency, UC Davis scientists have documented a decline in Lake Tahoe's clarity.** ***Right,*** **Brant Allen (middle) of TERC and Jeremy Sokulsky (top) of the Lahontan water board lower the Secchi disk into Lake Tahoe. While visibility is sometimes as deep as 130 feet, the trend is toward declining clarity.**

8-inch white disk until it can no longer be seen by the naked eye, yielding annual averages based on more than 30 measurements taken regularly over the course of each year (see figure).

The two main culprits in the clarity decline are excess nutrients and sediments. Nutrients — particularly phosphorus but also nitrogen — increase the growth of algae, which in turn absorb and scatter light. The growth rate of algae near the lake surface has quadrupled over the last 35 years (see figure, page 46). Sediments both carry nutrients and scatter light themselves, and more than 10 tons of sediment are added to the lake each year from sources including erosion from development, road dust and engine exhaust.

Contaminants enter the lake in streamflow and fall directly onto its surface from the air — and then they persist because the lake has such limited outflow that water stays for an average of 700 years.

Lake Tahoe: From research to policy

Nearly 40 years after UC Davis limnologist Charles Goldman established the Tahoe Research Group, concern over the lake's diminishing beauty culminated in the Lake Tahoe Presidential Forum. "This place is amazing. It's a national treasure that must be protected and preserved," Vice President Gore told the forum on July 26, 1997. President Clinton then announced that he had just signed an executive order to ensure greater cooperation among the many groups working to protect the lake. Today, UC Davis and 10 affiliated research institutions as well as 19 federal, state and local agencies are participating in a concerted effort to restore Lake Tahoe's clarity.

Now called the Tahoe Environmental Research Center (TERC), the research group Goldman founded is part of the UC Davis John Muir Institute of the Environment, which is dedicated to solving environmental issues by bringing together researchers, regulatory agencies and the public. Besides serving as an umbrella for UC Davis's Tahoe research, TERC facilitates collaboration with researchers elsewhere, notably the University of Nevada, Reno; the Desert Research Institute in Reno; and the Scripps Institution of Oceanography in La Jolla. A biennial science conference on Lake Tahoe met last in 2004; five of the many studies presented are published in this issue of California Agriculture (see pages 53-82). Its next meeting is in October 2006.

TERC is currently housed in a former fish hatchery in Tahoe City, Calif., an outdated facility

Heather M. Segale, UC Davis TERC

Alan Heyvaert (left) of the Desert Research Institute and John Reuter of the UC Davis Tahoe Environmental Research Center (TERC) monitor construction of a new 45,000-square-foot Tahoe Center for Environmental Sciences in Incline Village. The wetland site of the old facility, a former fish hatchery in Tahoe City, will be restored.

Sylvia Wright/ UC Davis

Role of lake mixing

Equally important is where all the contaminants go once they are in the lake. "The muck we see is in the top 300 feet," Swift says.

The destination of contaminant-laden streamflow depends on its temperature relative to the lake: when the streamflow is warmer, it shoots across the surface; when the streamflow is colder, it plunges toward the bottom. While contaminants can also settle to bottom, it takes years for the smallest particles to get there. And even then, they can come back up.

The analysis of satellite data has revealed that water jets rise from the depths and go shooting across the lake. The jets are several miles wide and "can go clear across the lake in half a day," says Geoffrey Schladow, a UC Davis environmental engineer who directs the Tahoe Environmental Research Center (TERC). "It took us by surprise." Driven by winter winds, these water jets typically mix the lake only about three-fifths of the way down, but every few years they mix it completely to the bottom.

Contaminants and visibility

The next step is determining how the contaminants affect visibility in the surface waters of Lake Tahoe. Swift and colleagues developed an optical model of the lake that predicts Secchi depths based on factors including algae and sediments (Aquatic Sciences, in press). The model showed that sediments account for more than half of the lake's clarity loss, and that the smallest particles (less than 8 microns) have the biggest impact.

In addition, the optical model accurately predicts seasonal dips in clarity that are observed in

For more info:

Pathway 2007 factsheet:
www.tiims.org/tiimswebsite/ContentProjects/Pathway2007/factsheets/Pathway2007.pdf

Tahoe Environmental Research Center:
http://terc.ucdavis.edu/index.html

For the first time, agencies are now coordinating their 20-year plans for Lake Tahoe

that has only 1,000 square feet of laboratory and office space. "Charles Goldman used to say, 'We're doing first-class research in a third-class facility'," says Heather Segale, TERC education and outreach coordinator.

But soon the researchers will also have a first-class facility, the Tahoe Center for Environmental Sciences, a joint project between UC Davis and Sierra Nevada College that is scheduled to be completed in August 2006 in Incline Village, Nev. Designed to be environmentally friendly, with features including plenty of natural light and solar panels, the 45,000-square-foot center also has ample common space to foster collaboration and the exchange of ideas among researchers.

To help inform policy, UC Davis and its affiliated institutions formed the Tahoe Science Consortium, which in August 2005 signed an agreement to work more closely with the federal and state resource-management agencies responsible for protecting Lake Tahoe. "At the science end, all the scientists will report to a representative board; the same is true at the policy end," Segale says. "Then the two boards will get together so the policymakers can ask key management questions, and the scientists can provide answers and direct research."

The agencies are also working more closely with each other, in a process called Pathway 2007. The main agencies overseeing Lake Tahoe are the Tahoe Regional Planning Agency, which was created by Congress in 1969 to regulate development on both the California and Nevada sides of the lake; the USDA Forest Service; the Lahontan Regional Water Quality Control Board, which is responsible for water quality on the California side; and the Nevada Division of Environmental Protection, which is responsible for water quality on the Nevada side.

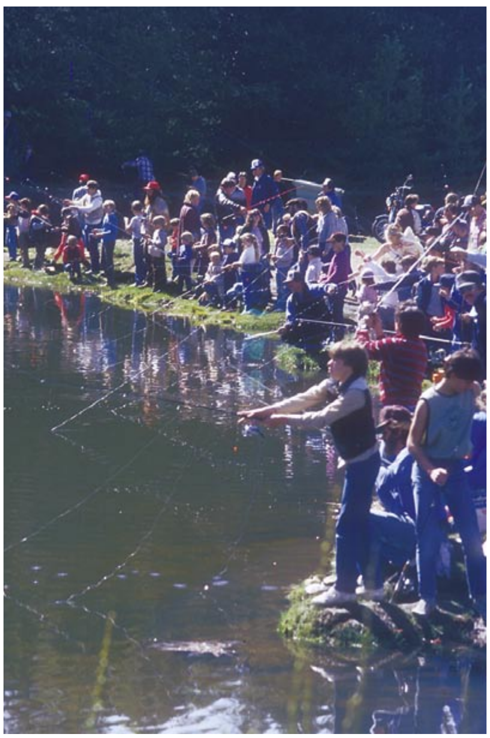
Adding to the mix, this spring UC will hire a Cooperative Extension natural resource advisor to conduct programs in the basin.

"For the first time, agencies are now coordinating their 20-year plans for Lake Tahoe," Segale says. — *Robin Meadows*

December and June. During winter, the top 150 or so feet of water cools and the wind then mixes the lake, bringing algae, nutrients and sediments up from deeper waters. During summer, the streamflow is relatively warm and so spreads across the lake's surface waters, concentrating the fine particles it carries there. "The small volume of stream water has an amplified effect on clarity," Swift says.

Based on the various factors that affect visibility, from contaminants to lake mixing to optics, TERC researchers developed a comprehensive clarity model that predicts Tahoe's Secchi depths. Contaminants from streams are estimated based on monitoring a subset of the 63 streams that feed into the lake, while contaminants from the air are monitored by the California Air Resources Board. Lake mixing is driven by the local weather, which is monitored by TERC. So far, the lake clarity model has been tested on Secchi depths that have already been observed. "The model agrees very well with the last 3 to 4 years of data," Schladow says. "Next we'll project the lake's clarity over the next 20 years under various management scenarios."

John Stumbos



Lake Tahoe's popularity as a tourist destination has increased substantially since the 1950s, bringing with it increased pressure on its limited resources. *Above*, a fishing derby at Sawmill Pond.

Restoring clarity

The current management goal, which was set by the Tahoe Regional Planning Agency (see sidebar, page 50), is to restore the lake's clarity to that of the early 1970s, when the Secchi depth was about 95 feet. However, whether this goal can be reached remains to be seen. "I think it's achievable to stop the decline and improve the clarity," Schladow says. "I don't know if we can reach 95 feet. It depends on what the model shows about the sources [of contaminants]."

One barrier to restoring Lake Tahoe is that the contaminant sources and their relative impacts are not yet fully understood. For example, while recent research shows that the atmospheric nutrients in the lake are primarily from within the Tahoe Basin (see page 53), the primary atmospheric sources of fine sediments remain unknown. If the latter are mostly from the Central Valley, they will be harder to control than if they are mostly from within the Tahoe Basin. "We need to identify where gains can be made," Schladow says.

Similarly, the relationships between Tahoe Basin land uses and lake clarity are not well understood. TERC researchers are currently investigating the effects of land uses — from forests (see page 65) and wetlands to development and ski areas. Recent research shows that local urban forests may affect biodiversity and ecosystem function (see page 59).

Another big unknown is how climate change will affect the lake's clarity. Temperatures in large lakes worldwide are rising about twice as fast as those in oceans, and UC Davis ecologist Robert Coats has found that Lake Tahoe has warmed nearly 0.9° F over the last 30 years. Warmer waters could mean less mixing, which could make clarity either better or worse: the former by keeping more nutrients in the depths, and the latter by not diluting sediments in the surface. "There are two competing processes," Schladow says. "We're learning not to be foolish enough to say 'this is going to happen next year'."

Warming could also favor different kinds of algae than those that currently dominate Lake Tahoe. While the lake has hundreds of algal species, only about a dozen dominate during any given time period and they can have very different effects on clarity. At its clearest, the lake was dominated by diatoms, which are compact and so scatter light less, but now the lake has lots of algae that have long filaments and so scatter light more.

Reasons for hope

Despite the progressive decline in clarity and the many unknowns, hope remains for restoring Lake Tahoe. There are still days when the lake is so clear that you can see to depths of 130 feet or more, and the annual clarity improves by as much as 3 feet during drought years, when streamflow and thus nutrient and sediment levels are low. This suggests that controlling erosion could have a huge impact, which makes sense because the lake has a natural cleaning process in that sediments eventually do settle to the bottom.

Encouragingly, erosion control may indeed be feasible in the Tahoe Basin. Recent research shows that fine sediments in runoff can be reduced by a combination of soil restoration and pine needle mulch (see page 72) as well as other treatments (see page 77). In addition, most of the wetlands around the lake have been lost to development, and restoring them is a promising way to keep sediments and nutrients from reaching the lake. "If we can bring these levels back down, the lake has a fair chance of regaining much of its fabled clarity," Swift says.

— Robin Meadows

REVIEW ARTICLE

RESTORING CLARITY

Local air pollutants threaten Lake Tahoe's clarity

by Alan W. Gertler, Andrzej Bytnerowicz, Thomas A. Cahill, Michael Arbaugh, Steven Cliff, Jülide Kahyaoğlu-Koračin, Leland Tarnay, Rocio Alonso *and* Witold Fraczek

In 2002, scientists constructed passive samplers throughout the Tahoe Basin, including, *above*, on Diamond Peak, to measure 2-week average ozone and nitric acid concentrations. Air pollutants are believed to be an important contributor to Lake Tahoe's declining clarity.

Lake Tahoe is a high-altitude (6,227 feet) lake located in the northern Sierra Nevada at the California-Nevada border. During the second half of the 20th century, the decline in Lake Tahoe's water clarity and degradation of the basin's air quality became major concerns. The loading of gaseous and particulate nitrogen, phosphorus and fine soil via direct atmospheric deposition into the lake has been implicated in its eutrophication. Previous estimates suggest that atmospheric nitrogen deposition contributes half of the total nitrogen and a quarter of the total phosphorus loading to the lake, but the sources of the atmospheric pollutants remain unclear. In order to better understand the origins of atmospheric pollutants contributing to the decline in Lake Tahoe's water clarity, we reviewed a series of studies performed by research groups from the U.S. Department of Agriculture's Forest Service, UC Davis and the Desert Research Institute. Overall, the studies found that the pollutants most closely connected to the decline in Lake Tahoe's water quality originated largely from within the basin.

The Lake Tahoe Basin is a subalpine ecosystem bordered by the Carson Range to the east (Nevada) and the Sierra Nevada crest to the west (California). This 520-square-mile basin is dominated by the 192-square-mile Lake Tahoe, which is noted for its exceptionally clear water. The lake's water clarity is largely due to nutrient-poor granitic soils in the surrounding watershed and a low watershed-to-lake ratio. Most of the rest of the basin is a nitrogen-poor, mixed-conifer forest ecosystem comprised mainly of fir (red [*Abies magnifica*] and white [*Abies concolor*]), pine (lodgepole [*Pinus contorta*], sugar [*Pinus lambertiana*] and Jeffrey [*Pinus jeffreyi*]), and incense cedar (*Calocedrus decurrens*). Historically, these factors have minimized the flow into the lake of nutrients and sediment that could reduce water clarity.

Since 1967, Lake Tahoe's water quality has declined at an unexpectedly rapid rate, in part due to anthropogenic nutrient and sediment loading (Goldman 1988; Jassby et al. 1999; Murphy and Knopp 2000). The Lake Tahoe Watershed Assessment provided a comprehensive summary of scientific knowledge regarding the factors contributing to the observed water-quality decline and the steps that can be taken to restore the Lake Tahoe Basin ecosystem (Murphy and Knopp 2000). Contributing factors include nitrogen, phosphorus and sediment flow into Lake Tahoe. Murphy and Knopp (2000) reported that atmospheric deposition (gases and particles that enter the lake from the air) accounts for approximately 55% of the nitrogen and 27% of the phosphorus load into the lake. No estimate of atmospheric fine-soil particulate input was presented.

GLOSSARY

CALMET/CALPUFF air-quality modeling system: A meteorological and air-quality model adopted by the U.S. Environmental Protection Agency as the preferred model for assessing the long-range transport of pollutants.

Eutrophication: The process by which water bodies receive excess nutrients that can stimulate plant and algal growth.

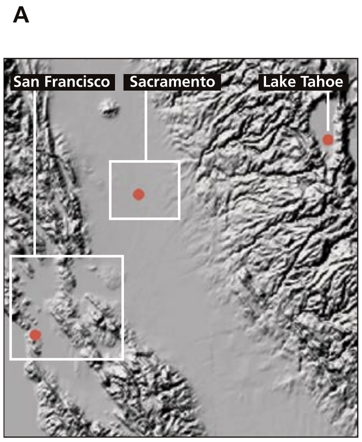
Foliar injury: Injury of tree foliage caused by exposure to elevated concentrations of ambient ozone.

Nested domains: Different-sized geographical areas used in the modeling system. To reduce computational requirements, the outer domain is modeled using larger areas, while the resolution is enhanced for the inner (nested) regions of interest.

Prognostic numerical weather model (MM5): The Fifth-Generation Penn State/National Center for Atmospheric Research meteorological model. This model is used to predict wind speed and direction for use in other modeling systems such as CALMET/CALPUFF.

Sensitivity studies: Tests performed as part of the modeling validation process to assess which variables can affect model performance.

Synoptic: Reflecting overall patterns derived from data obtained simultaneously from points across a wide area.



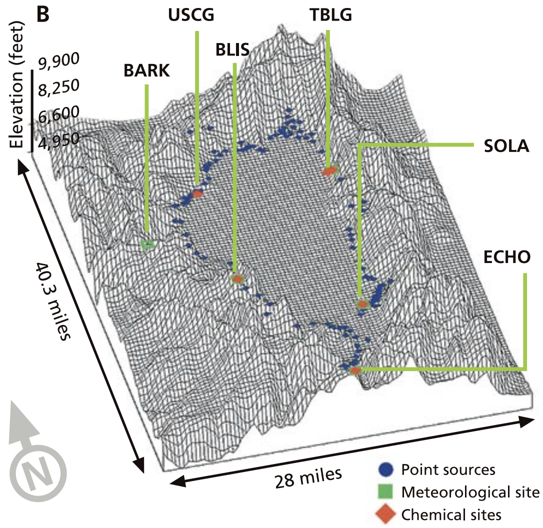


Fig. 1. (A) Area of California modeled, with emissions sources (San Francisco Bay Area, Sacramento and Lake Tahoe Basin). (B) In the Lake Tahoe Basin, blue circles designate point sources used to represent mobile and area emission sources. Marked stations are South Lake Tahoe (SOLA), Bliss State Park (BLIS), Thunderbird Lodge (TBLG), Echo Summit (ECHO), U.S. Coast Guard (USCG) and Barker Pass (BARK).

In addition to decreasing water clarity, atmospheric pollutants can affect forest health. It is well established that ambient ozone has pronounced adverse effects on forest health in California's mountain regions (Arbaugh et al. 1998). According to large-scale distribution maps of the Sierra Nevada bioregion, the Lake Tahoe Basin's summer-season, 24-hour ozone levels are 50 parts per billion (ppb) to 60 ppb (Fraczek et al. 2003). Such ozone levels may be phytotoxic (toxic to vegetation) (Krupa et al. 1998) and can adversely affect tree health (Arbaugh et al. 1998). Ozone causes foliar injury (an indicator of tree health) to ponderosa (*Pinus ponderosa*) and Jeffrey pines in the central Sierra Nevada (Miller et al. 1996), including in the Lake Tahoe Basin (Pedersen 1989).

While there has been extensive water sampling in the basin, air sampling has been limited to two sites at the southern end of the basin, and does not include data on phosphorus or coarse soil particles. Atmospheric deposition could be a major source of nitrogen input and a significant source of both phosphorus and sediment loading, but we lack knowledge regarding the sources and concentrations of these pollutants, the contributions from in-basin versus out-of-basin sources, and the spatial distribution and deposition of atmospheric pollutants. In this paper, we review the air-quality study results that address these questions (NWRA 2004).

Jack Kelly Clark

Using atmospheric models, the authors simulated how air pollutants from the Bay Area, *above*, and Sacramento Valley are affecting the Tahoe Basin. While pollutants are transported from outside the basin, the model suggests that they are significantly diluted by mixing on the western slopes of Sierra Nevada.

Modeling nitrogen pollution

In terms of hemispheric atmospheric circulations, California is within the latitude range of prevailing westerly winds. However, due to the relatively weak effect of large-scale atmospheric motions, wind patterns tend to be modified by the differential heating between the land and ocean. Previous studies have shown that in California's typical summer wind-flow pattern, marine air penetrates through the Carquinez Strait (in the northeastern San Francisco Bay) and bifurcates around the Bay's Delta region into south and north branches (Moore et al. 1987; Zaremba and Carroll 1999). This primary pattern is superimposed by thermally driven daytime upslope and nighttime downslope flows, making pollutant transport eastward possible from heavily polluted regions, such as the San Francisco Bay Area and the Sacramento Valley, up into the Sierra Nevada.

In order to quantify how much nitrogen these winds bring into the Tahoe Basin, we used the advanced numerical atmospheric models CALMET/CALPUFF (Scire et al. 2000) and MM5 (Grell et al. 1995) to estimate the contributions from both in-basin (such as cars and trucks) and out-of-basin (such as industry, cars and trucks) nitrogen sources. The area we modeled was selected to simulate how the basin's air is affected by pollutant transport from the Sacramento Valley and San Francisco Bay Area (fig. 1A).

In this study, the comprehensive CALMET/CALPUFF air-quality modeling system was coupled with a numerical weather model called MM5. The output from the MM5 model was coupled with available surface and upper-air meteorological measurements to enhance the accuracy of the predictions (fig. 1B). The CALMET/CALPUFF simulation grid (fig. 1A) contained 250-by-265 cells, each 1 square kilometer (0.61 square miles), and the lower

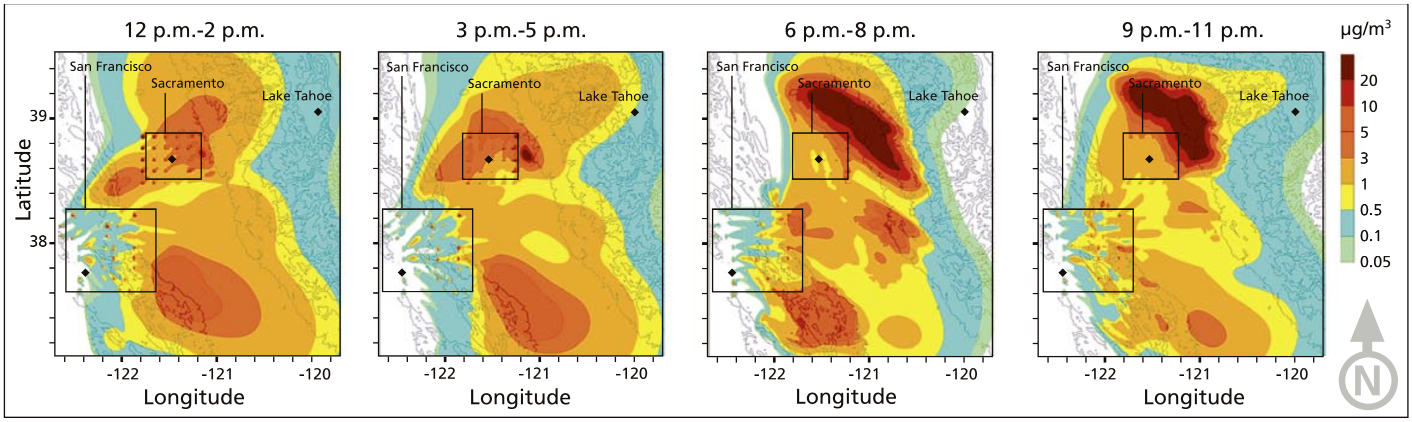


Fig. 2. Evolution of nitric acid (μg/m³) plume from California's Central Valley, Aug. 28, 2000. Concentrations (filled contours overlaid with topography) are averaged over 3-hour intervals. The enclosed areas surrounding Sacramento and San Francisco regions designate the emission sources. Note the effects of daytime upslope flows and nighttime downslope flows; pollutant concentrations at elevated regions are low, implying minimal nitric acid transport to the Lake Tahoe Basin.

left grid corner was referenced at 37.10° N and 122.70° W.

In order to accurately predict regional versus local transport and dispersion, information on pollutant (such as oxides of nitrogen) emission rates was critical. This data was obtained from the California Air Resources Board (CARB). For the Lake Tahoe Basin, we prepared hourly emission allocations based on the CARB inventory. Hourly emissions from Truckee, Reno, Interstate 395 and the west Sierra foothills were also included. Sensitivity studies were performed for the model calibration.

One of the key pollutants leading to nitrogen deposition into the lake is nitric acid (HNO_3). This pollutant is not directly emitted from sources but is formed through a series of atmospheric reactions involving oxides of nitrogen and hydrocarbons. Estimates of nitric acid formation and atmospheric concentrations were made using the previously described modeling system.

Simulations were performed for three selected cases coinciding with previous nitric acid measurements during summer 2000 (Tarnay et al. 2001, 2005). These cases were selected based on a range of wind patterns and high/low ambient nitric acid. Analysis of surface observations (surface wind frequencies and precipitation) and large-scale synoptic pressure systems (500 millibar wind and pressure maps) showed that the selected cases were climatologically representative of summer 2000. MM5 simulations were performed with two-way nesting for a 4-day period. The spin-up time was 12 hours. In order to model regional-scale transport and reduce the effect of boundary conditions, the CALMET/CALPUFF modeling system was run for 72 hours for each of the selected cases.

Airborne plume mostly diluted

The overall simulation results indicated that there is pollutant transport from the Sacramento Valley and San Francisco Bay Area to the Lake Tahoe Basin (fig. 2). However, these pollutant concentrations were significantly diluted by mixing with other air masses on the west slopes of the Sierra Nevada at increasing elevations, as measured in previous studies (Carroll and Dixon 2002; Dillon et al. 2002; Bytnerowicz et al. 2002). While part of the emissions plume can progress over the Sierra Nevada to the Lake Tahoe Basin, nitric-acid ambient air concentrations are extremely low. In addition, later in the day, downslope winds carry the plume back to the Central Valley. (Simulations of in-basin and out-of-basin emissions were performed separately in order to determine their relative contributions; the impact from in-basin emissions is not shown in figure 2.)

On the other hand, the results also showed that the predicted nitric acid concentrations due to local sources were in good agreement with actual measurements. For example, 90% of the predicted nitric acid concentrations were due to local sources, and the predicted concentrations comprised 65% of the average measured values (Tarnay et al. 2001) in all the monitoring locations around Lake Tahoe. Emissions of nitrogen oxides from other nearby source regions such as Reno and Interstate 80 were two to three orders of magnitude smaller than those from the San Francisco Bay Area and the Sacramento Valley, and had no significant predicted impact.

In short, while the results of this work suggest that daytime pollutant transport from upwind of the Lake Tahoe Basin appears to be likely, the amount of nitric acid transported from outside of the basin is much less than that from in-basin sources. In order to better quantify these contributions, additional study is needed on long-term transport effects under different meteorological patterns that could lead to increased transport to the basin.

Measuring ozone and nitric acid

On-ground monitoring of pollutant concentrations helps to test the results of the modeled air-pollution distribution predictions. One of the great difficulties in evaluating the transport of air pollutants into the Tahoe basin is the lack of monitoring data on the upwind western slope of the Sierra Nevada. We were able to address this problem by using inexpensive passive samplers, which allowed us to deploy a monitoring network of unprecedented scope throughout the region. To provide measurements in support of the meteorological modeling described in the previous sections, we studied two pollutants: ozone (O_3), long

Out-of-basin sources are not the major contributors to observed pollutant levels.

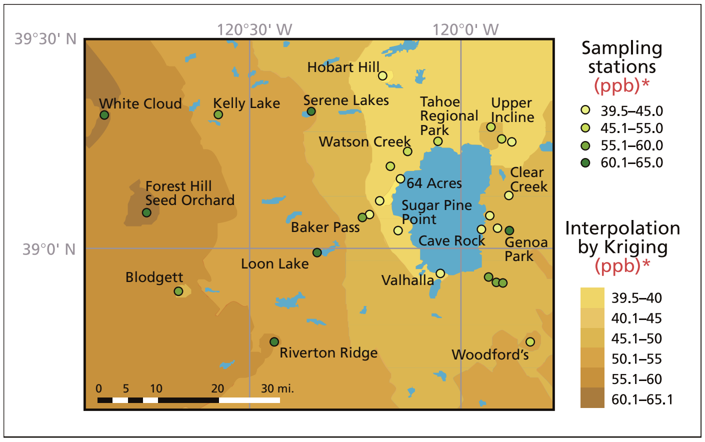


Fig. 3. Seasonal average distribution of ambient ozone concentrations (ppb)* in the Lake Tahoe Basin and its vicinity, summer 2002. Shaded areas represent concentrations determined by interpolation of the observed data by Kriging. Maximum levels of ozone were observed to the west of the lake, but are not transported to the basin.

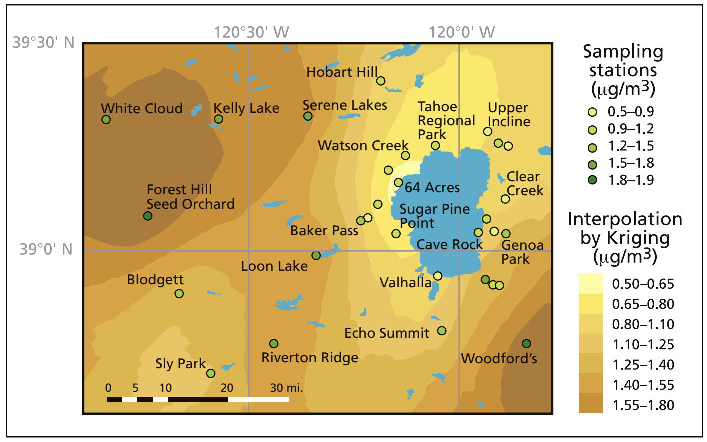


Fig. 4. Seasonal average distribution of ambient nitric acid concentrations (μg/m^3) in the Lake Tahoe Basin and its vicinity, summer 2002. Maximum levels were observed west of the Sierra Nevada crest and lowest levels are near the west shore of the lake.

***Top,* UC Davis professor Tom Cahill sets up a DRUM sampler at South Lake Tahoe. *Bottom,* the sampler shows the pattern of very fine, phosphorus-rich aerosols collected over a 3-week period. The dark bands occur in the morning and evening, when the wind stagnates.**

known to transport into the basin, and nitric acid. We selected 32 monitoring sites to assess air pollution levels in and around the Lake Tahoe Basin. The sites were selected in open terrain located on a western aspect, with free air movement from all directions. The passive samplers measured 2-week average ozone and nitric acid concentrations throughout the 2002 smog season.

Pollutant distribution maps were developed with geostatistical software (ARC/INFO Geostatistical Analyst; ESRI, Redlands, Calif.) that uses values measured at sample points at different locations in the landscape and interpolates them into a continuous surface. Using a set of measurements in a given study area, a spatial model of ozone concentration was constructed (Fraczek et al. 2003). Techniques were then used to develop prediction maps of the air pollutant's distribution for each individual 2-week sampling period and for the entire season.

The highest 2-week and whole-season average ozone and nitric acid concentrations occurred in the Sacramento foothills, west of the Lake Tahoe Basin. Concentrations of these pollutants were much lower near the lake, especially near the west shore. It appears that the mountain range west of the Lake Tahoe Basin (Desolation Wilderness) impedes the westerly flow of low-layer polluted air masses from the Sacramento metropolitan area and the Sierra Nevada foothills, limiting pollutant transport into the basin. East of the lake, ozone and nitric acid levels generally increased with distance from the South Lake Tahoe community urban area.

Over the course of smog season, there was a clear pattern in ozone and nitric acid concentrations. For the entire study area, the lowest levels occurred during the first halves of July and October, and the highest levels occurred during the second half of August (figs. 3 and 4). The highest levels of ozone and nitric acid in August coincide with traffic-related high emissions of nitrogen oxides and volatile organic compounds (VOC), high temperatures and solar radiation — all factors promoting the generation of these photochemically produced air pollutants.

Foliar injury rates low

To estimate the effects of elevated ozone on forest health, we reviewed the results of studies conducted by the USDA Forest Service in the 1970s. USDA scientists conducted studies to evaluate foliar injury, applying the Ozone Injury Index (OII) methodology, in the Sierra Nevada and the San Bernardino mountains (Miller et al. 1996). Foliar ozone injury was evaluated at 25 preexisting study sites in the Lake Tahoe Basin. The sites were originally established in the late 1970s to each contain 15 mature ponderosa pine trees, but as few as six of the original trees remained at some of the locations by the time of the foliar-injury evaluation study.

Overall, 23% of the trees evaluated had foliar ozone injury but the average OII was only 17.3 (100 indicates the highest level of injury), which shows that the injury occurring to the pines in

*Corrected from printed version.

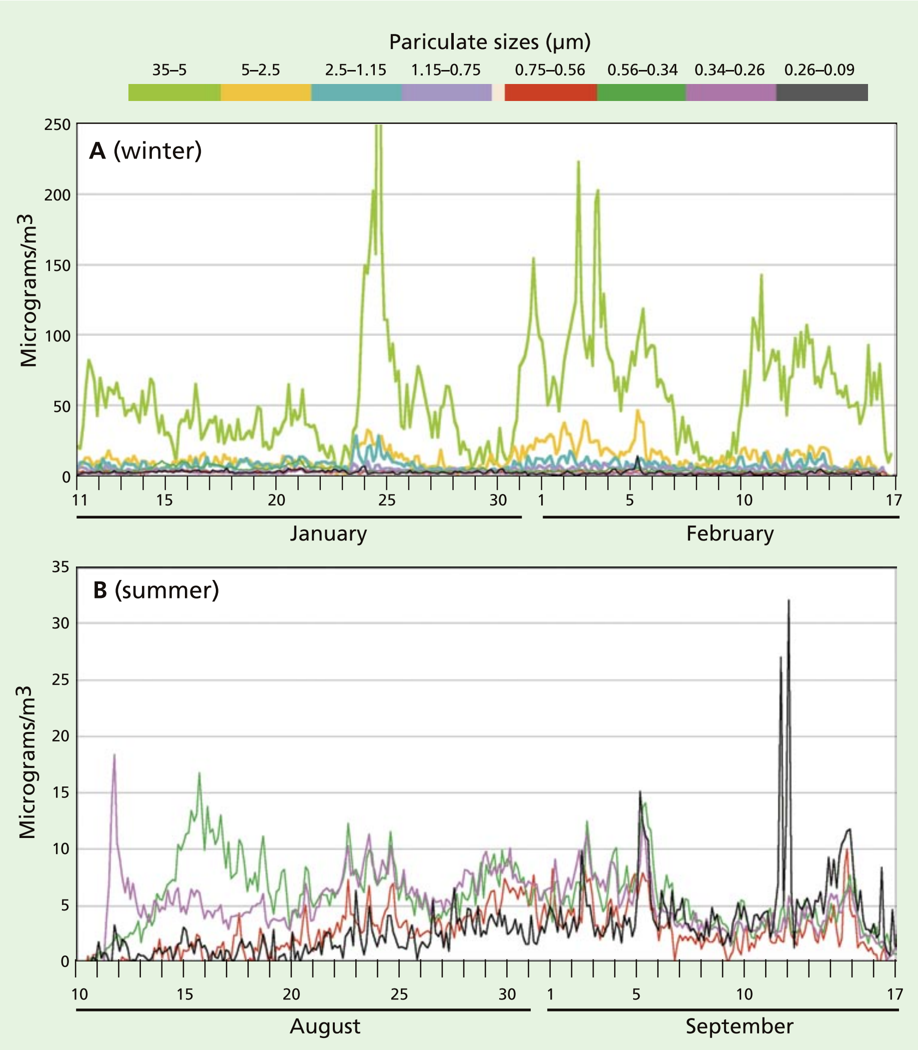


Fig. 5. Size-segregated phosphorus measurements (μg/m^3) in 2002 for (A) winter (eight particulate size fractions) and (B) summer (four fine particulate size fractions to better show smoke and exhaust). The maximum levels of phosphorus were observed in the largest size fractions, winter and summer, indicating that resuspended geological material was the major pollutant source.

TABLE 1. Sources and estimated tonnage of phosphorus deposition in the Lake Tahoe Basin

Transported	Ton/year
Asian dust	0.6–1.0
Sacramento Valley dust	0.12–0.6
Oregon forest fire smoke (2002)	0.2–0.3
Local	
Highway road dust (winter)	3.5–5.0
Local soils (spring to fall)	1.5–4.5
Vehicle exhaust	1.2–1.8
Local wood smoke	0.3–0.5

this area is slight. In addition, no discernible spatial patterns of injury were observed between sites, so the degree of ozone injury likely depends on microsite growing conditions as well as on the genotypic and phenotypic responses of individual trees to ozone air pollution.

Measuring phosphorus

Phosphorus, which comes into the lake from both sediment in stream runoff and airborne particles, is presently the limiting nutrient for algal growth, a major factor in the lake's clarity decline; while all pollutants entering Lake Tahoe must be reduced, nitrogen pollution is currently so high that the most effective strategy for the time being is to reduce phosphorus. About one-fourth of all phosphorus comes from the air, as shown by the phosphorus data from deposition buckets on and near the lake, but phosphorus is rarely seen in the existing ambient air samples. One possibility is that phosphorus occurs in particles larger than those collected by current in-basin, filter-based air samplers, which only measure fine particles below 2.5 microns (μm) in diameter.

In order to assess the airborne sources of phosphorus, measurements were performed in January and August 2002 using a particulate sampler developed at UC Davis (Cahill and Wakabayashi 1993). In contrast to filter-based measurements, this sampler allowed for measuring particles in eight size-segregated fractions, ranging from 35 μm (roughly a high-volume [Hi-Vol] inlet to catch coarse soil aerosols) to 0.09 μm (to catch diesel and smoking car exhaust). In addition, the UC Davis particulate sampler allowed for better source identification because it has a high time resolution (3 hours). Finally, this sampler resulted in an order of magnitude better detection of phosphorus than the filters (Bench et al. 2002) because elemental analysis for phosphorus was performed by synchrotron X-ray fluorescence (S-XRF). Samples were collected at the South Lake Tahoe site for 12 weeks in winter and 6 weeks in summer to allow analysis of synoptic weather patterns.

Most of the phosphorus observed during the winter and summer occurred between the 2.5 and 35 μm size fractions, consistent with the sources being resuspended road dust and soil (fig. 5). Previous studies in the area used samplers with a 2.5-μm upper cut-point and would have missed this contribution. This implies that most of the phosphorus comes from in-basin sources, since particles in this range tend to deposit rapidly and so are rarely transported far in the atmosphere. We can estimate the phosphorus deposition from a range of sources based on these particulate sampler data and earlier data using the Lake Tahoe Airshed Model (LTAM) (Cahill and Cliff 2000) and estimated deposition velocities (Seinfeld and Pandis 1998) (table 1).

While these results are highly uncertain, especially because they are based on a single, near-roadway South Lake Tahoe site, together they imply that the majority of phosphorus deposition in the Tahoe Basin can be attributed to local sources from roadway sanding and salting in winter, local soils in summer and vehicle exhaust. Furthermore, some of the out-of-basin sources may not occur routinely. The 2002 Oregon forest fires were unusually severe, and showed a high phosphorus content not seen in less violent fires such as prescribed burns (Turn et al. 1997). The Asian dust values in particular are uncertain and highly variable from year to year, depending on the strength of the dust storms in Asia and the location of the Pacific high-pressure system and winds, which can push Asian dust north into Canada and cut off transport to California, as happened in 2003. It should also be noted that these measurements represent total phosphorus, as opposed to bioavailable phosphorus, and thus have uncertain impacts on algal growth.

Sources of Tahoe air pollutants

Taken together, our review of several important studies indicates that out-of-basin sources are not the major contributors to the observed levels of air pollutants in the Lake Tahoe Basin. For example, the advanced numerical modeling approach found that 90% of predicted nitric acid in the basin came from precursors emitted within the basin. The models attributed the minimal contribution from out-of-basin sources to a number of factors, including dilution, dispersion and minimal pollutant flow into the basin. Similar conclusions were reached by the studies investigating forest health and the sources of phosphorus in the Lake Tahoe Basin. Based on these findings, the most effective strategy to reduce the impact of atmospheric deposition on the lake's clarity and in-basin forest health would be to control local pollutant emissions.

Phil Schermeister

Out-of-basin pollutants are not the major contributors to air pollution in the Tahoe Basin; rather, local sources are having the most significant effects on air and water quality, and forest health. *Above,* Highway 50 in South Lake Tahoe.

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RESEARCH ARTICLE

RESTORING CLARITY

Biotic diversity interfaces with urbanization in the Lake Tahoe Basin

by Patricia N. Manley, Dennis D. Murphy, Lori A. Campbell, Kirsten E. Heckmann, Susan Merideth, Sean A. Parks, Monte P. Sanford *and* Matthew D. Schlesinger

Phil Schermeister

Development since the 1950s and 1960s has had important effects on animals and plants around Lake Tahoe, in California and Nevada. The authors studied a diversity of taxa to evaluate the role of urban forests in supporting biodiversity.

In the Lake Tahoe Basin, the retention of native ecosystems within urban areas may greatly enhance the landscape's ability to maintain biotic diversity. Our study of plant, invertebrate and vertebrate species showed that many native species were present in remnant forest stands in developed areas; however, their richness and abundance declined in association with increasing development across all taxonomic groups. Species richness for land birds and mammalian carnivores declined with development, whereas ant richness and small mammal abundance peaked at intermediate levels of development. Vegetation structure simplified with increasing development and the exotic plant species increased. The results of this study, the first to consider the effects of urbanization and remnant forests on biotic diversity in the Lake Tahoe Basin, can be used to guide land-use planning in order to maintain and enhance biodiversity in the face of increasing urbanization.

After almost a century of resource extraction, the 1950s and 1960s brought rapid development to the Lake Tahoe Basin that fragmented formerly large and contiguous wildlands, with the resulting parcels converting to urban uses (Lindström 2000). Concern about the diminishing beauty and ecological integrity of Lake Tahoe has led to substantive changes in resource management and land-use planning. For example, the Tahoe Regional Planning Agency, created in 1969, imposed land-use regulations that slowed the pace of urbanization and changed development patterns. In addition, over the past two decades, the U.S. Forest Service, California Tahoe Conservancy and Nevada Division of State Lands have acquired more than 9,000 parcels (totaling approximately 20,000 acres) of environmentally sensitive lands in an effort to maintain and protect their ecological integrity, thereby reducing threats to the clarity of Lake Tahoe and the integrity of its watershed.

The Tahoe Basin is particularly vulnerable to the loss of biotic diversity because of its topography and geography. Lake Tahoe sits in an isolated montane basin with a broad elevational range; as such, it supports narrow bands of three distinct life zones nested within a relatively small geographic area. Development is most prevalent near the lake, therefore species restricted to the lower montane zone adjacent to the lake (under 7,500 feet) are particularly vulnerable to the direct and cumulative impacts of urbanization.

Urbanization can alter the biodiversity of native forest habitat at both site and landscape scales, such as decreasing the richness of native species, losing vulnerable species (such as habitat specialists, dietary specialists and large-bodied species), and increasing generalist and exotic species (Hansen et al. 2005). Our study evaluates the species richness and relative abundance of multiple taxonomic groups along a gradient of surrounding urbanization to provide a fundamental indication of the effect of urbanization on biotic diversity in lower-montane remnant forests.

Sampling for plants and animals

We selected sample sites surrounded by varying degrees of urban land use and road density (fig. 1). Using ArcGIS

Birds showed the strongest response to development. Species that frequently cohabit with humans such as, *top right*, the house finch and, *bottom right,* Steller's jay, responded well to development, while less-abundant species like, *left,*the pileated woodpecker declined.

(ESRI 2002), we created a grid of 100-by-100-foot pixels across the entire basin and estimated the percentage development within each pixel based on land uses represented on county parcel maps. Development within 1,000 feet of each pixel (70-acre area) ranged from zero to more than 75% developed. Sample sites were randomly selected from the available 100-by-100-foot pixels within defined levels of development and basin orientations (north, south, east and west). All sample sites were centered within a native forest stand at least 1 acre in size.

Birds, mammals, ants and plants were sampled at up to 101 sites in 2003 and 2004. Of these sites, 68 were sampled for all four or more taxonomic groups. Field methods encompassed a variety of detection and descriptive methods.

Land birds were sampled using point counts; 10-minute counts were conducted during three visits to five stations located 650 feet apart per site. Bird species richness was based on the suite of terrestrial, nonraptor species detected across the five point-count stations; average relative abundance per count per site was based on all detections within 325 feet of each count station averaged across all stations and visits per site.

Small mammals were sampled using 64 Sherman live traps configured in a 350-by-350-foot grid. Traps were baited with oats and seeds, and checked twice a day for four consecutive days. The relative abundance of each species was calculated as the number of first captures per 100 trap nights; the abundance of deer mice *(Peromyscus maniculatus)* was only recorded on a random subset of 50 sites. Shrews (*Sorex* spp.) and voles (*Microtus* spp.) were analyzed at the genus level to avoid errors associated with identification to species.

Larger-bodied mammals were sampled using a combination of baited track plate stations and baited camera-detection stations spaced 820 feet apart per site (one each at the center).

Ground-dwelling ants were sampled using 12 pitfall traps arrayed in a 130-by-165-foot grid. Richness and relative abundance values were based on all individuals captured at each site.

The composition, structure and percentage cover of vegetation were characterized using a combination of standard measurement methods, including circular plots, quadrats, and line-intercept and point-intercept transects.

While the Tahoe Basin is not greatly developed — certainly when compared to many truly urban locations in the West — our results showed responses to even limited development at species and community levels in every taxonomic group.

Species richness and abundance

Birds. Patterns of species richness and abundance varied among taxonomic groups, with birds showing the strongest response to development. We detected 21,726 individual birds of 68 native land bird species. Species richness ranged from 16 to 37 per site (average = 27.1, s.d. = 4.45) and declined significantly with development (adjusted [adj.] $R^2 = 0.327$, $P < 0.001$) (fig. 2), and richness based on the center point alone (such as, primarily in native forest) also declined significantly with development (adj. $R^2 = 0.178$, $P < 0.001$).

The richness of many bird species groups — ground nesters, shrub nesters, overstory tree nesters, primary cavity excavators, bark foragers, foli-

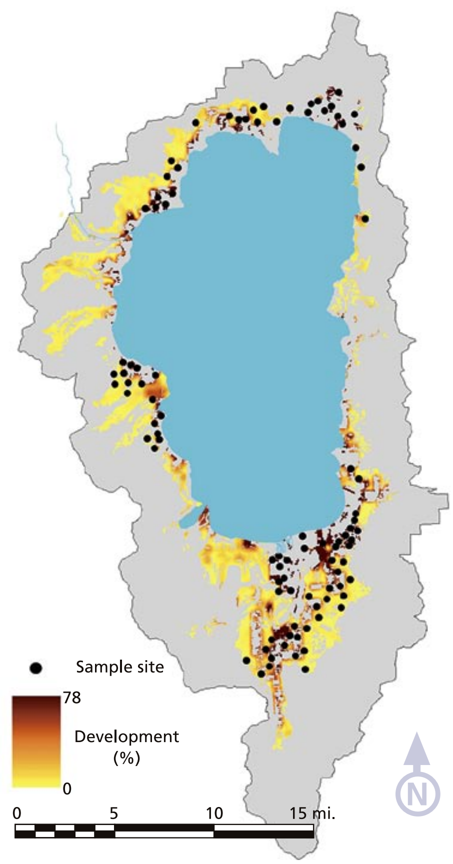

Fig. 1. Sample sites were located throughout the Lake Tahoe Basin.

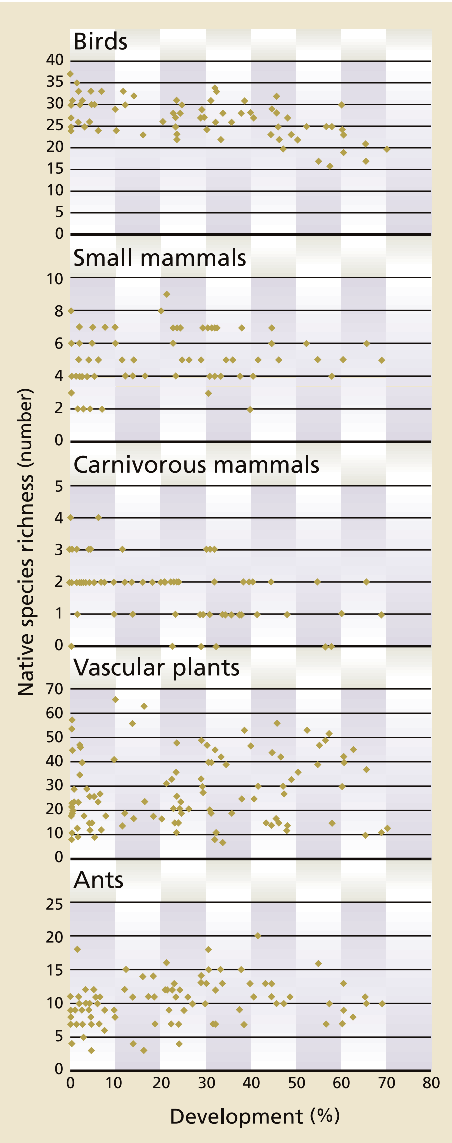

Fig. 2. Number of species detected relative to percentage development within a 1,000-foot radius around 72 to 101 sites sampled for five taxonomic groups in 2003 and 2004, in the Lake Tahoe Basin.

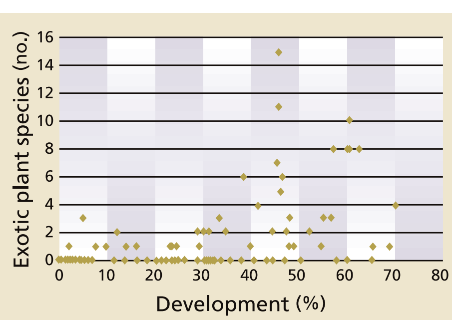

Fig. 3. Number of exotic plant species relative to percentage development within a 1,000-foot radius around 101 sites sampled in 2003 and 2004, in the Lake Tahoe Basin.

Eighteen small mammal species were captured and identified; the species richness declined with development, while their relative abundance peaked at intermediate development levels. *Clockwise from top left:* California ground squirrel, Douglass squirrel, vole and chipmunk.

age foragers and invertivores — also was negatively related to development. Conversely, bird abundance, which ranged from 7.6 to 34.5 individuals per count (average = 19.3, s.d. = 4.30) increased with development (adj. R^2 = 0.064; P = 0.016), but individual species varied widely in their abundance relative to development. Over 50% of the 68 native bird species in the sample showed a significant change in abundance with development: 12 species increased and 24 decreased.

Responding positively to development were species that frequently cohabit with humans, including Steller's jay *(Cyanocitta stelleri)*, American robin *(Turdus migratorious)* and brown-headed cowbird *(Molothrus ater)*, as well as cliff swallow *(Petrochelidon pyrrhonota)* and Brewer's blackbird *(Euphagus cyanocephalus)*. The 24 species that declined with development included less-abundant species associated with older forests, such as pileated woodpecker *(Dryocopus pileatus)*, hermit thrush *(Catharus guttatus)*, brown creeper *(Certhia americana)* and hermit warbler *(Dendroica occidentalis)*, as well as species that were not expected to be as sensitive to development, such as dusky flycatcher *(Empidonax oberholseri)* and olive-sided flycatcher *(Contopus cooperi)*.

Small mammals. More than 23,000 trap nights (average = 238.5 per site, s.d. = 26.00) for small mammals resulted in the capture of 4,755 individuals representing 18 species. Species richness ranged from two to nine per site (average = 5.2, s.d. = 1.59). We found no significant difference in the richness of small mammal species along the development gradient (adj. R^2 = 0.011, P = 0.385); however, variablity in species richness appeared to decrease with development (fig. 2). The average number of individuals captured per 100 trap nights per site, excluding deer mouse, ranged from 3.2 to 54.9 individuals (average = 19.7, s.d. = 10.98). On average, over 95% of these individuals were squirrels and chipmunks (average = 19.1 individuals per site, s.d. = 11.12).

We found that the relative abundance of small animals peaked at intermediate levels of development (40% to 50%), as reflected in the quadratic regression (adj. R^2 = 0.231, $P < 0.001$). Of the 11 species and genera that were detected at more than one site, the abundance of three was positively, and significantly, associated with development: California ground squirrel *(Spermophilus beecheyi)*, Douglas squirrel *(Tamiasciurus douglasii)* and voles (adj. R^2 = 0.054, P = 0.028, adj. R^2 = 0.117, P = 0.002, and adj. R^2 = 0.310, $P < 0.001$, respectively). One species, shadow chipmunk *(Tamias senex)*, was negatively associated with development, but not significantly (adj. R^2 = 0.034, P = 0.068). Four additional species exhibited a threshold effect: they were not detected where development exceeded more than 30% (shrews and

Bobcat, skunk, bear: E. Lee Fitzhugh/UC Davis

Courtesy of John White © 2004

The richness of the native large mammal species found declined significantly with development; *top,* bobcat and striped skunk were most sensitive, followed by, *bottom left,* black bear. *Bottom right,* coyote was consistently detected regardless of the development level.

shadow chipmunk) or 40% (golden-mantled ground squirrel [*Spermophilus lateralis*] and lodgepole chipmunk [*T. speciosus*]).

Large mammals. Ten carnivore species were detected: eight native species, domestic dog (*Canis familiaris*) and domestic cat *(Felis catus)*. The most frequently detected native species were coyote (*C. latrans*) (n = 34 sites), black bear (*Ursus americanus*) (n = 35) and raccoon (*Procyon lotor*) (n = 37), with each species detected at more than 40% of sample units. The least frequently detected species were bobcat (*Lynx rufus*) (n = 2 sites), weasels (*Mustela* spp.) (n = 2) and spotted skunk (*Spilogale putorius*) (n = 3).

Native species richness ranged from zero to four per site (average = 1.7, s.d. = 0.95), and it declined significantly with development (adj. $R^2 = 0.062$, $P = 0.016$) (fig. 2). Even when detection data were limited to the center point (such as within native forest), richness declined with development (adj. $R^2 = 0.055$, $P = 0.016$). Marten *(Martes americana)*, small weasels, bobcat and both skunk species *(S. putorius* and *Mephitis mephitis)* appeared to be the most sensitive to development, with the few detections located at sites with 15% or less development. Black bear was intermediate in its response to development, with frequency of detection greatest at sites with 30% or less development and detections peaking at sites with limited development (1% to 15%). Coyote and raccoon are both commonly considered amenable to human development, and they each had a fairly consistent frequency of detection across sites with more than 1% development. As expected, domestic dog and cat detection frequencies increased with development. Domestic cats were only detected at sites with more than 15% development. Domestic dogs, however, were the most frequently detected species across sample units; they were detected at 64% of sites, and at 87.8% of sites with development greater than 15%. At one sample site, at least 13 distinct individual dogs were recorded during one 10-day survey period.

Ants. A total of 32,023 ants representing 46 species were detected; subfamilies with the greatest species richness were Formicinae (30 species) and Myrmicinae (13 species). The most frequently detected species were *Formica sibylla* (16% of sites), *F. obscuripes* (11%) and *Camponotus modoc* (9%). Species richness ranged from 3 to 20 (average = 10.1, s.d. = 3.19), and was greatest at intermediate levels of development (40% to 50%) (fig. 2). A quadratic regression showed a significant relationship between ant species richness and development (adj. $R^2 = 0.128$, $P = 0.002$).

Ant abundance across all species was not significantly associated with development ($P = 0.193$), but a general decline in maximum abundance with development was apparent. Responses were also observed in the two specialist functional groups of ants that we examined (ground nesters [n = 9 species] and log nesters [n = 5]). Although the maximum richness of log nesters declined with development, overall richness did not decline significantly ($P = 0.899$), and ground nester abundance reached its peak at intermediate levels of development and had a significant quadratic relationship with development (adj. $R^2 = 0.131$, $P = 0.001$).

Plants. No significant relationship was observed between development and the richness of all 209 native plant species we detected (average = 28.3, s.d. = 14.47, range = 7 to 66) (fig. 2) or for four of five life-form groupings: shrubs, trees, annual herbs and perennial herbs. The exception was native perennial grass richness, which increased significantly with development (adj. $R^2 = 0.14$, $P < 0.001$). The richness of exotic plant species (n = 41), not surprisingly, also increased significantly with development (adj. $R^2 = 0.251$, $P < 0.001$) (fig. 3). Sites with 40% or less development had three or fewer exotic species (with one exception) and averaged 0.5 exotic species (s.d. = 0.97) per site, whereas sites with more than 40% development had as many as 15 exotic species and averaged 3.7 exotic species (s.d. = 3.95) per site. The five most frequently occurring exotic species were cheatgrass (*Bromus tectorum*) (15.3% of sites), orchard grass (*Dactylis glomerata*) (14.4%), dandelion (*Taraxicum officinale*) (12.7%), wheatgrass (*Elytrigia pontica*) (9.3%) and knotweed (*Polygonum arenastrum*) (6.8%).

Elements of vegetation structure were affected by development. The average percentage cover of native shrubs,

Courtesy of Alex Wild @ 2004

Ant species richness peaked at intermediate levels of development.

Trees, shrub, flowers: John Stumbos

The richness of native plant species was not generally associated with development, while exotic, nonnative species richness increased significantly. *Left to right,* native trees, shrubs and flowers; *right,* a nonnative dandelion.

perennial herbs and annual herbs did not change with development; however, the average percentage cover of native trees declined with development (adj. $R^2 = 0.070$, $P < 0.001$), and the average percentage cover of native perennial grasses increased with development (adj. $R^2 = 0.131$, $P < 0.001$). Tree density did not change significantly with development based on each of three diameter classes: 5 to 11 or fewer inches, 11 to less than 24 inches, and 24 or more inches diameter at breast height. These results suggest that although tree densities were not significantly altered, canopies were reduced by development. Snag density and log volume also declined with development (adj. $R^2 = 0.170$, $P < 0.001$, and adj. $R^2 = 0.127$, $P < 0.001$, respectively). In addition, less developed sites had older, more decayed snags (based on average decay classes) than more developed sites (adj. $R^2 = 0.080$, $P = 0.005$).

Urban forests and biotic diversity

The effects of development on biotic diversity in the Lake Tahoe Basin, as in rural environments in general, have not been well documented (Hansen et al. 2005). It is generally accepted that lands converted to residential and commercial uses exhibit more compromised ecological processes than do less intensively developed lands (Marzluff and Ewing 2001); however, even in less urbanized areas, such as the Tahoe Basin, the spatial and temporal progression of development can significantly alter species composition and distributions (Hansen et al. 2005).

We observed changes in plant community composition and structure in every taxonomic category, but responses varied among species groups and individual species. In some groups we observed changes in species richness, while others showed responses in individual species abundances. Species losses are typically preceded by reductions in species abundances through a myriad of causal factors; thus, patterns of abundance within and among species can foretell pending local attrition of species. In our study, many responses showed a high level of variance, indicating that development is one of many factors affecting species composition and abundance in these remnant forests. Native land birds and mammalian carnivores appeared to be affected most by development, exhibiting reductions in species richness, even in native forests. While reductions in native land bird species richness have been observed in response to development in a variety of ecosystems (Germaine et al. 1998; Fernández-Juricic 2000), species richness of native carnivore assemblages is rarely evaluated; rather, carnivore species responses have been evaluated individually. In our study, declines in bird and carnivore richness were concomitant with both increases and decreases in the frequency of occurrence and abundance of individual species.

Most of the bird species that showed a strong negative response to development were associated with older forests and/or forest understories, suggesting that vertical complexity and understory conditions are important factors that determine the diversity of land bird communities; human disturbance and increased predation may also be contributing factors. As we observed, many native carnivores, even opportunistic species such as the black bear, can be less prevalent or absent in areas where development has replaced and fragmented habitat (Odell and Knight 2001; Crooks 2002). Larger mammals require specific conditions for den and rest sites that are less likely to be present in more developed and disturbed forested areas; however, urban forests may provide valuable foraging habitat for larger mammals. Conversely and not surprisingly, domestic dogs and cats were consistently more prevalent in areas with human development, and their impacts on native species occurrence and abundance can be significant (Miller et al. 2001; Odell and Knight 2001).

Impacts to largely ground-dwelling animal species were observed across multiple taxonomic groups, including changes in small mammal and ant communities with greater landscape development. Positive responses to development were most common among species most closely associated with forest canopy (such as tree squirrels), whereas specialized ground associates (such as shrews) were not observed in areas with higher levels of development. Ants and small mammals showed peaks in richness or abundance at intermediate levels of development; others have observed such peaks in small mammals (Racey and Euler 1982) and ants (Nuhn and Wright 1979), as well as other taxonomic groups (McKinney 2002).

We did not see major changes in plant species composition and vegetation structure with development; for example, plant species richness within forest fragments was not substantially

Development within the Tahoe Basin still takes up a limited proportion of the landscape, but responses to development occurred within every taxonomic group studied.

different along the development gradient. At a glance, this is surprising given that native plant species richness is usually thought to be reduced by urbanization (Whitney 1985); however, in the lower montane forests of the Lake Tahoe Basin, many plants are dispersed and pollinated by wind, and are capable of dispersing over large distances and across unsuitable terrain. For plants, therefore, it may be the condition of the greater landscape that is the primary determinant of the composition of species at any individual site.

It is possible that the responses we observed in plants (and to lesser degrees in other taxonomic groups) may reflect the fact that development within the basin still occupies a relatively limited proportion of the landscape, even within the lower montane zone where we conducted our study. (In fact, we sampled nearly all of the forest fragments that had over 60% development within 1,000 feet and were at least 2.5 acres.) Even the most-developed sites were usually in close proximity to areas with lower levels of development. Through that lens, native plant species richness in forest fragments within the basin may reflect larger-scale changes in landscape condition. Certainly it is not surprising that sites with higher levels of development appear more vulnerable to invasion by exotic plants, and they are likely to serve as staging areas for the dispersal of non-natives into less fragmented and less disturbed lower montane forests (Luken 1997). Understanding the conditions and thresholds associated with invasions by non-natives could help inform urban forest management to improve conditions for native species, while reducing the risks of invasion by exotic plant species.

The Tahoe Basin is not greatly developed — certainly when compared to many truly urban locations in the West — but our results showed responses to even limited development at species and community levels in every taxonomic group. This is the first study that has attempted to quantify the effects of development on biotic diversity and the contribution that urban forests make to supporting biotic diversity in the Lake Tahoe Basin. It only begins to build an understanding of how development is affecting ecological communities and species both common and rare, and what mechanisms are determining the observed changes. Our observations suggest that the effects of development on biotic diversity may not be linear, but rather that certain significant shifts in species composition and abundances occur at lower levels of development. Accordingly, this may be an opportune time to evaluate the risks, opportunities and consequences of various land-use planning options to the conservation of biotic diversity in the Lake Tahoe Basin.

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Nutrients flow from runoff at burned forest site in Lake Tahoe Basin

by W. Wally Miller, Dale W. Johnson, Theresa M. Loupe, James S. Sedinger, Erin M. Carroll, James D. Murphy, Roger F. Walker *and* Dallas Glass

The long-term trend toward decreased water clarity in Lake Tahoe is well documented, and is strongly linked to increased nitrogen and phosphorus loading from surrounding watersheds. Recent research has detected very high concentrations of biologically available nitrogen and phosphorus in overland/litter interflow from Sierra ecosystems. The objective of this study was to assess the effect of a localized wildfire on the nutrient content of such runoff. The wildfire increased the frequency and magnitude of elevated nutrient concentrations in discharge runoff for all three parameters studied (nitrate nitrogen, ammonium nitrogen and phosphate phosphorus). Although the mobilization of nutrients was increased due to wildfire, the lack of O horizon material (the surface organic layers of mineral soils) after burning may ultimately reduce discharge concentrations over time.

Fire suppression and the lack of forest thinning have led to dense, overgrown forests throughout the Sierra Nevada and Lake Tahoe Basin.

Although highly variable across the stand, downed and dead fuel loading now commonly exceeds 616,000 pounds per acre in some locations.

The long-term trend toward decreased water clarity in Lake Tahoe is well documented, and is strongly linked to increased nitrogen and phosphorus loading (Goldman 1989; Goldman et al. 1990; Jassby et al. 1999) (see page 49). If we are to arrest further deterioration of the lake's famed clarity, it is essential to recognize that its water quality is directly linked to upland watershed processes, including nutrient cycling, groundwater and stream flow, surface runoff, precipitation type (rain vs. snow, intensity and duration), atmospheric deposition and anthropogenic manipulation (such as fire and fire suppression) (Reuter and Miller 2000).

Fire suppression, in particular, has caused a decline in overall forest health due to the buildup of high tree densities and heavily vegetated understory; ladder fuels, which provide vertical continuity between surface fuels and crown fuels in a forest stand; downed timber fuels; and deepened forest floor, particularly the thickened O horizon (surface organic layers of mineral soils). It is a commonplace belief throughout the Tahoe Basin and Sierra Nevada that forests long protected by fire suppression contribute little in the way of natural nutrient discharge, because nutrient uptake and interception are maximized by the thick understory accumulation (Reuter and Miller 2000).

Nonetheless, recent Sierra research has detected very high concentrations of biologically available nutrients in the overland/litter interflow taking place above the mineral surface at the interface between surface deposits of decomposing organic litter and the underlying, often water-repellent, mineral soil surface (Miller et al. 2005).

GLOSSARY

Biologically available: That portion of a chemical compound or element that can be readily taken up by living organisms.

Discharge flux: The time rate of transport of a quantity (e.g., mass or volume of a fluid) across a given area (volume flow per unit time per unit area).

Litter/mineral surface interface: The boundary between surface deposits of decomposing litter materials (O horizon) and the underlying mineral soil surface (A horizon).

Mineralization: The conversion of organic nutrients to inorganic compounds. This process is typically accomplished by various soil microbes but may also be induced by fire. Once mineralized, such nutrients are present in soluble inorganic form and subject to biotic uptake, infiltration and leaching, and/or runoff discharge.

Nutrient: Elements or compounds essential as raw materials for organism growth and development, such as nitrogen and phosphorus, that are often present in soluble inorganic forms such as nitrate nitrogen, ammonium nitrogen and phosphate phosphorus.

Nutrient concentration and loading: Concentration is the amount of a given nutrient per unit of solution, whereas loading is an absolute amount. Both are used as indicators of water quality degradation, but the absolute amount of pollution is often considered more important.

Nutrient cycling: The circulation or exchange of elements, such as nitrogen, phosphorus and carbon dioxide, between nonliving (e.g., the soil) and living (e.g., plants, microorganisms) portions of the environment. The process includes all inputs such as wet and dry atmospheric deposition, plant litter fall and decay; internal cycles such as mineralization and plant uptake; outputs such as leaching, volatilization and runoff discharge; and biotic (biomass incorporation) and abiotic (soil) storage.

Nutrient, labile: Soluble inorganic nutrient forms such as nitrate, ammonium nitrogen and phosphate phosphorus, that are readily transformed by microorganisms, readily available to plants and easily transported by water flow.

Overland flow/litter interflow: Overland flow is runoff water moving across the land surface; litter interflow is runoff water moving within surface deposits of organic litter above the organic/mineral soil interface.

Soil profile and horizonation: The soil profile is a vertical sequence of well-defined layers of soil, sediment or decaying vegetation; soil horizons are layers of organic or mineral materials lying approximately parallel to the land surface with physical, chemical and biological properties that are distinct from the adjacent layers. Soil horizon designations include the O horizon (layers dominated by organic materials), A horizon (mineral layers that formed at the land surface or are located immediately below the O horizon), B horizon (the mineral subsurface horizon formed and lying below the A horizon) and C horizon (subsurface mineral horizons, excluding bedrock, that are little affected by pedogenic soil-forming processes).

The nutrients found by Miller et al. (2005) at high concentrations included: nitrate nitrogen (NO_3^--N) at up to 95.4 milligrams nitrogen per liter (ppm), ammonium nitrogen (NH_4^+-N) at up to 87.2 milligrams nitrogen per liter (ppm); and phosphate phosphorus (PO_4^{3-}-P) at up to 24.4 milligrams phosphorus per liter (ppm). These levels suggest that the nutrient ions in runoff must be derived from the well-developed surface organic layers in fire-suppressed forests. Also, it suggests that there has been little contact between the organically derived nutrients and the underlying mineral soil surface — where ammonium nitrogen and phosphate phosphorus would normally be removed from solution by direct interaction with soil particles — thereby reducing soluble discharge concentrations.

The buildup of fuels in the understory has also increased the potential for catastrophic wildfires, and wildfire certainly affects the various nutrient pools available for waterborne transport. The objective of this study was to assess the effect of a localized wildfire on the nutrient content of surface runoff.

A wildfire clearly has the potential to cause an immediate adverse impact on discharge water quality.

Wildfire provides opportunity

Location and setting. The study location was a 29.6-acre (12-hectare) parcel located 1.24 miles (2 kilometers) southeast of the south shore of Lake Tahoe, near Stateline, Nev. (57° 30′ latitude and 119° 55′ longitude). The vegetation was overgrown, and the dominant overstory consisted of decadent (trees deteriorating due to age) white fir (*Abies concolor* Gord. & Glend.), Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) and lesser amounts of sugar pine (*Pinus lambertiana* Dougl. [Strobus L. Mold.]). The understory was dominated by Sierra chinquapin (*Chrysolepis sempervirens* [Kellogg] Hjelmq), currant (*Ribes* spp.) and minor amounts of snow bush (*Ceanothus velutinis* Dougl. Ex Hook.) and bitterbrush (*Purshia tridentata* [Pursh] DC). The soils developed on granitic parent material and belong to the Cagwin-rock outcrop complex found on predominantly north-facing slopes of 10% to 40%. Total average annual precipitation (1984 to 2004) across the basin is about 31.9 inches (81 centimeters) (TIIMS 2005).

Plots. Sixteen 0.10-acre (0.04-hectare) study plots were established in 2001 for a study originally designed and instrumented to examine the effects of mechanical harvest and prescribed fire, and their interaction (two-by-two-by-four replications) with forest health, nutrient cycling and discharge water quality. On July 3, 2002, the Gondola wildfire altered the study by fully burning seven (nos. 10 to 16) of the 16 previously established research plots and partially burning two more (nos. 8 and, very minimally, 9). We were thus given the seldom-afforded opportunity to study post-wildfire effects on nutrient discharge in runoff, compared to that from adjacent unburned controls (fig. 1).

Runoff collectors. Runoff collectors (Miller et al. 2005) had been installed in four plots (nos. 1 to 3, and no. 14) prior to the wildfire (September and

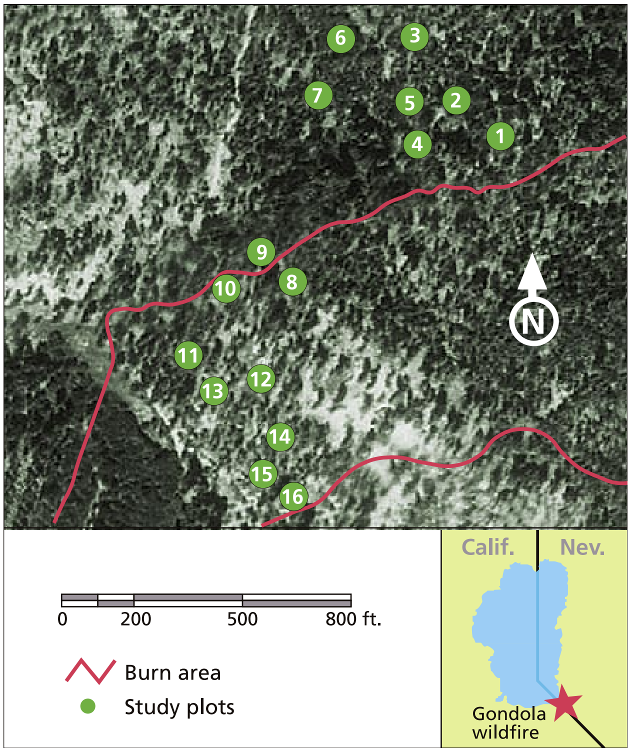

Fig. 1. The study site and Gondola wildfire location.

Data from runoff collectors, *above*, shows that runoff from overland/litter interflow seeps downslope through the organic surface layers during rainfall and snowmelt, never gaining enough momentum to cause physical disturbance.

November 2001), and were reinstalled in each of the 16 plots about 4 weeks after the burn once access to the site was allowed. They consisted of a buried bucket container slightly larger than 2 gallons (8 liters) fitted with a collection funnel, vent-stack roof flashing, screen and high-density polyethylene cover (fig. 2). The top of the collection funnel was located approximately 2 inches (5 centimeters) below the soil surface, and the roof flashing was aligned perpendicular to the slope either at the soil surface of the bare or burned soil for the collection of overland flow, or at the litter/mineral soil interface for the collection of litter interflow.

Incidental runoff. Construction of the collectors was such that incidental runoff could be generated on the impermeable surface of the collector itself over a 0.39-inch-by-3.54-inches (1-by-9 centimeters) flow path (1.4 square inches; 9 square centimeters). Incidental runoff is derived from sources other than natural processes of overland/litter interflow; for example, the impermeable surface of the runoff collector itself. For an average annual precipitation of 31.9 inches (81 centimeters), this would result in a maximum of 730 milliliters of incidental runoff. Direct vertical infiltration of precipitation into the 0.07-square-inch (0.43-square-centimeter) V-notch opening itself could account for another 35 milliliters, for a total of about 770 milliliters per year of incidental runoff not attributable to natural processes. For cumulative collections far exceeding 770 milliliters per year, we can think of no explanation other than that of in situ overland flow/litter interflow in the form of surface runoff.

Data collection. For purposes of data comparison, plot no. 9 was grouped with the unburned treatments and plot no. 8 with the burned treatments. The runoff collectors were checked twice monthly during the winter and spring months (December through April) when access was possible, and following each rainfall event during the summer and fall (May through November). When present, runoff from overland flow or litter interflow was retrieved from the collection containers using a Model Change C pump (Soil Moisture Corp.). Total volume was measured and a subsample was retained for chemical analyses. The subsamples were filtered through a 1.8×10^{-5}-inch (0.45 μm) filter (Osmonics Laboratory Products) and analyzed at the Soil, Water and Forage Analytical Laboratory of Oklahoma

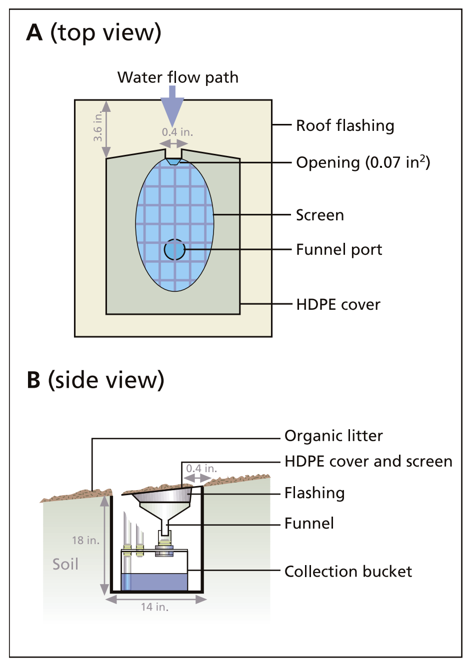

Fig. 2. Runoff collectors were developed to test the premise that natural overland flow from heavily forested ecosystems is an unimportant source of water and nutrient discharge from upland Sierra forests. Source: Miller et al. 2005.

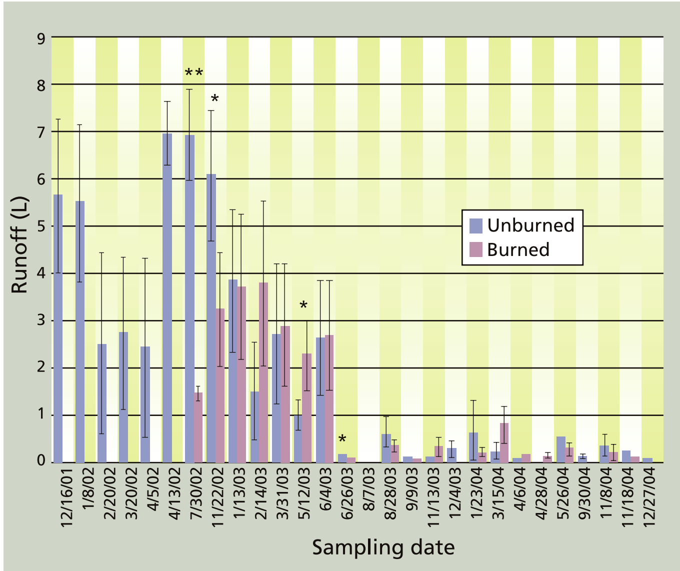

Fig. 3. Mean runoff collected from burned and unburned study plots; the Gondola fire was July 3, 2002. Error bars are for standard error; *t*-test significance differences are noted as *P* < 0.10 (*) or *P* < 0.05 (**) (1,000 milliliters [mL] = 1.0 liter = 0.265 gallon).

State University (Stillwater, Okla.). The nutrients were analyzed on a Lachat flow-injection analyzer using the salicylate method for ammonium nitrogen (SSSA 1996), the cadmium reduction method for nitrate nitrogen (US EPA 1979) and the ascorbic acid method for phosphate phosphorus (US EPA 1979).

Data analysis. We were unable to collect samples from each plot on every sampling occasion because of periodic soil-water repellency, the erratic weather patterns over the study area and unavoidable field damage from animals. Consequently, a mixed models analysis was performed on the postwildfire data only. Our design included fixed plots, randomly placed within the burned and unburned areas (n = 8 plots in each area). Because each plot was sampled repeatedly during the study, we treated plots as repeated random effects in the analysis. Treatment was a fixed effect (burned versus unburned). Samples were classified as being from winter (December through April) or summer (May through November), so we included season as a second fixed effect. We included the volume of runoff as a continuous covariate.

Hypotheses for each dependent variable (ammonium nitrogen, nitrate nitrogen and phosphate phosphorus) were then analyzed separately using a mixed models procedure, with plots as the random effect, treatment and season as fixed effects, and runoff volume as a covariate. We considered previously conceived combinations of the fixed and random effects and the covariate as potential hypotheses to explain patterns in the dependent variables. The only interaction we considered was that between treatment and season. Models were analyzed using PROC MIXED in SAS (SAS Institute 2004).

Runoff and nutrient mobilization

We measured the mean interflow runoff from four unburned plots (nos. 1 to 3, and no. 14) prior to the July 3, 2002, wildfire and eight unburned plots (nos. 1 to 7, and no. 9) following the wildfire, and overland flow runoff from eight burned plots (no. 8, and nos. 10 to 16) (fig. 3). The total (not per sampling event) amount of collector-derived incidental runoff over the 36-month period following the wildfire — from July 30, 2002, to Dec. 27, 2004, — could account for only about 0.61 gallon (2.31 liters; 2,310 milliliters) of the cumulative runoff measured. Therefore, cumulative values greater than 2.31 liters were attributed to on-site, natural overland or litter interflow.

Variability was high because runoff was not present in every collector at each sampling date. However, *t*-test comparison of the overall data (not presented) showed runoff volumes to be significantly greater ($P < 0.05$) during the winter and spring (December to April), compared to summer and fall collections (May to November). This trend is typical of Sierra ecosystems.

The first two samplings following the wildfire (one during a summer rain event, July 30, 2002, and another in fall, Nov. 22, 2005) showed significantly less runoff from the burned plots. In the unburned areas, water repellency is typically found at the litter / soil surface interface boundary (Bashir 1969), is most pronounced during late summer and early fall (July and August, October and November) and diminishes over winter (Burcar et al. 1994). Lower initial runoff from the burned area may have been due to the fire-induced development of a 2-inch (5-centimeter) layer of wettable soil above a subsurface water-repellent layer in the burned areas. This effect has been reported in the literature (DeBano 1969), and is caused by intense heat that volatilizes the organic coatings on the mineral surfaces, which then recondense with depth. Once the wettable layer has saturated (such as during snowmelt) one would expect at least comparable runoff from the burned areas. This was generally the case, with few significant differences observed between treatments thereafter.

The concentrations of nutrients in the surface runoff for the unburned and burned plots following the wildfire were also highly variable (fig. 4A–C). *T*-test analysis showed that the only consistently significant ($P < 0.05$) treatment (unburned / burned) effect was for phosphate phosphorus, where concentrations in the surface runoff were greater from the burned areas the first year following the wildfire (fig. 4A). Although not significant for either of the nitrogen forms because of the variability among individual plots over time, the trend was similar in that both ammonium and nitrate nitrogen concentrations in the runoff from burned plots were generally higher than from the unburned controls (figs. 4B and 4C).

The nutrient concentrations that we found were much greater (two to three orders of magnitude) than those typically reported for Tahoe Basin tributaries and the lake itself (Reuter and Miller

Heavy surface accumulations of decomposing, layered organic deposits, *right,* are now predominant in the Tahoe Basin and can be as high as 83,000 pounds per acre in some areas.

2000; Miller et al. 2005). Furthermore, visual comparison of the data suggests that there is a seasonal trend to periods of elevated nutrient discharge, with the highest concentrations typically associated with runoff collected during the summer months. For example, runoff volumes were at times significantly lower in the summer (hence a concentration effect) compared to the larger amounts collected during winter precipitation and snowmelt (December through April). This apparent seasonal trend in nutrient discharge concentrations remained following the wildfire; but compared to the unburned controls, the effect of wildfire appears to have increased the frequency and magnitude of elevated summertime nutrient discharge concentrations for all three parameters, at least during the first season following the wildfire event.

Evaluating observational results

We used an information theoretic approach to assess hypotheses about the roles of fixed effects, random effects and covariates in explaining variations in the dependent variables (Burnham and Anderson 2002). Briefly, this approach simultaneously considers multiple competing hypotheses and evaluates the weight of evidence supporting each. The method relies on the use of Akaike's information criterion (AIC), described by: AIC = –2 × 1n(L) + 2K; K is the number of parameters in the statistical model and L is the likelihood for the model (estimated by PROC MIXED). We then used model weights (which indicate the probability that a given model is the best among a set of models considered), to estimate the strength of evidence supporting a particular model. Parameter estimates (such as differences between treatments) and their confidence intervals were used to indicate the strength of the effects we considered (such as burn effects). This approach is increasingly being applied in ecological studies and is considered the most appropriate for evaluating hypotheses in observational studies such as ours (Burnham and Anderson 2002).

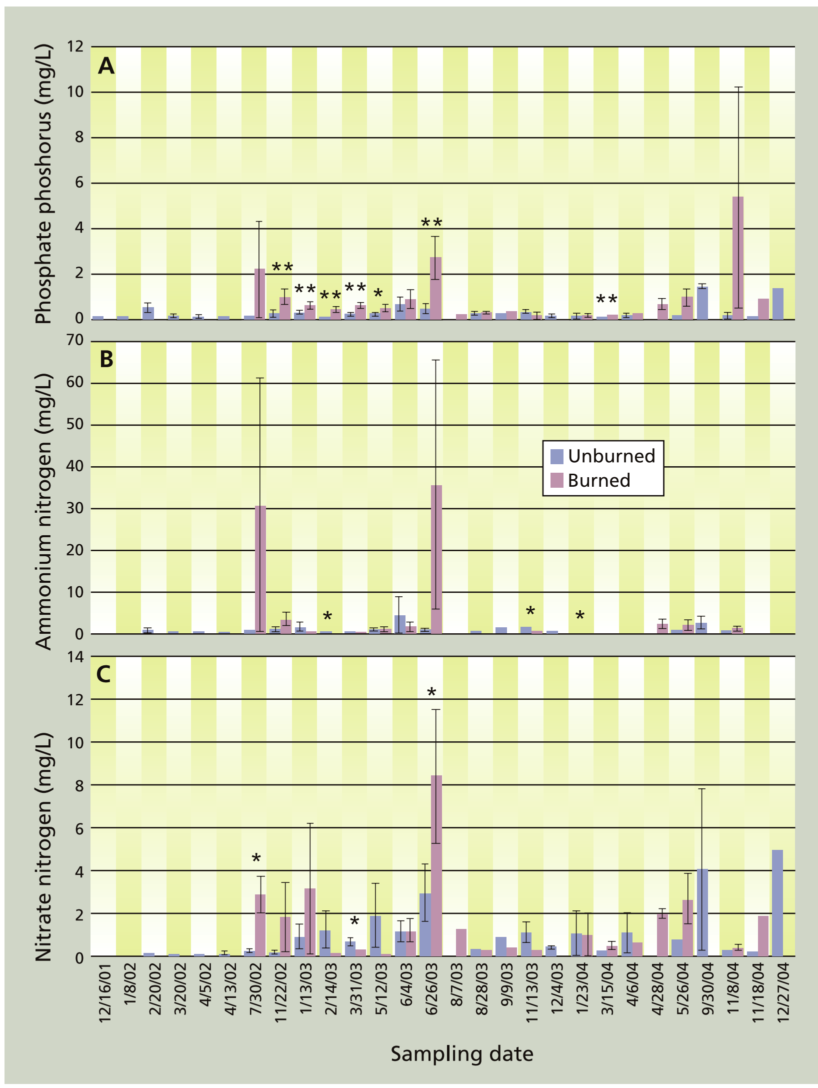

Fig. 4. Mean (A) phosphate phosphorus, (B) ammonium nitrogen and (C) nitrate nitrogen concentrations in runoff from burned and unburned plots; the Gondola fire was July 3, 2002. Error bars are for standard error, and significance differences are noted as $P < 0.10$ (*) or $P < 0.05$ (**) (milligrams [mg] per liter = 8.3 × 10^{-6} pounds per gallon).

Parameter estimates for the treatment-only model were significant for runoff concentrations of phosphate phosphorus ($P < 0.05$) and to a lesser extent nitrate nitrogen ($P < 0.10$), but not ammonium nitrogen. For the season-only model, parameter estimates were significant for runoff concentrations of phosphate phosphorus ($P < 0.05$) and to a lesser extent ammonium nitrogen ($P < 0.10$), but not for nitrate nitrogen. For example, mean runoff concentrations of phosphate phosphorus were 0.51 ± 0.22 milligrams of phosphorus per liter (ppm) lower from unburned compared to burned areas, and 0.46 ± 0.21 milligrams of phosphorus per liter (ppm) lower in winter compared to summer runoff.

The sum of AIC weights for a given model parameter is indicative of the overall importance of that parameter in explaining variation in the dependent variable (Burnham and Anderson 2002) (table 1). For phosphate phosphorus, model weights indicated that the relative importance of treatment was about 87%, compared to 65% for season and 43% for runoff volume. For ammonium nitrogen, the relative importance of treatment and season were comparable at 65% and 61%, respectively, while the effect of runoff volume was not as well supported (38% of model weight). The pattern was somewhat different for nitrate nitrogen in that runoff volume (91% of model weight) was the most important predictor, followed by treatment (60% of model weight) and season (48% of model weight). This may be related to the fact that, unlike the other ions, nitrate nitrogen is not adsorbed to the mineral fraction of soils and is therefore more strongly affected by solution dynamics. In any case, wildfire clearly appears to affect the concentrations of nutrients in runoff discharge through enhanced mobilization, likely the result of temperature-induced mineralization.

A worst-case scenario?

There is now evidence in many Sierra watersheds that fire suppression has resulted in a heavy buildup of a nutrient-rich forest floor (approximately 83,228 pounds per acre [93,200 kilograms per hectare]) (Murphy et al. 2006), and that slow leaching and runoff of this nutrient-rich material can be a significant long-term source of biologically available nitrogen and phosphorus (Loupe 2005). In the pre–fire suppression era, the organic mat was thinner, and the equilibrium for annual nutrient mineralization and discharge flux was also lower. On the other hand, the post–fire suppression era has resulted in the excessive buildup of much-thicker, nutrient-rich organic residues in heavily forested watersheds; in turn, there has been less nutrient volatilization and external dispersion. Although the litter mass is certainly a major sink for total nutrients, the mineralized nutrient content also increases proportionately in fire-suppressed forests. At our study location, the equilibrium has apparently shifted so that the annual amount of internal nutrient cycling increased, causing the organic mass to release more available nutrients into solutions passing through it (Loupe 2005).

Wildfire seems to further increase the immediate mobilization of labile nutrients (nutrients readily available to microorganisms and plants), and at least some of this labile nitrogen and phosphorus may well make it off-site during precipitation or snowmelt. The magnitude of such discharge cannot be quantified at this time because we have no means of determining the volume flow on an areawide basis. While wildfire causes a dramatic increase in nutrient mobilization, we have not found the same effect with cooler-

TABLE 1. Comparison of predictive models explaining solute concentrations in runoff at Gondola wildfire study site, Stateline, Nev.*

Dependent variable	Predictive model†	Delta AIC	AIC weight	Parameters estimated	-2 log likelihood
Phosphate phosphorus (PO_4^{3-}-P)					
	T	0	0.190	4	486.7
	T, S	0.3	0.164	6	495.2
	T, S, T×S	0.4	0.156	7	480.6
	T, V	0.6	0.141	5	485.1
	T, S, T×S, V	1.1	0.110	8	479.1
	T, S, V	1.2	0.104	7	481.4
	S	2.2	0.063	5	486.7
	S, V	2.6	0.052	6	485.0
	V	4.5	0.020	5	489.1
Ammonium nitrogen (NH_4^+-N)					
	S	0	0.179	3	1,409.9
	T, S	0.1	0.170	4	1,407.9
	T	0.4	0.146	3	1,410.3
	T, S, T×S	0.7	0.126	5	1,406.4
	S, V	1.4	0.089	4	1,409.2
	T, V	1.6	0.080	4	1,409.5
	V	1.6	0.080	3	1,411.6
	T, S, V	1.7	0.076	5	1,407.5
	T, S, T×S, V	2.4	0.054	6	1,405.9
Nitrate nitrogen (NO_3^--N)					
	T, V	0	0.263	6	854.8
	V	0.2	0.238	5	857.1
	T, S, V	1.3	0.138	7	853.9
	T, S, T×S, V	1.3	0.138	7	853.9
	S, V	1.4	0.131	6	856.2
	T, S	3.9	0.037	5	860.9
	S	4.5	0.028	4	863.6
	T	5.8	0.014	5	862.8
	T, S, T×S	6.1	0.012	6	860.9

* Information theoretic approaches (AIC) were used to compare and evaluate models. Delta AIC represents the difference in AIC between the best model considered and other models. AIC weight indicates the probability that a particular model was best among those considered. Model hierarchy for each dependent variable is presented in descending order of best-to-least fit model.

† T = treatment, S = season, V = runoff volume and T×S = treatment-by-season interaction. The sum of AIC weights for a given model parameter is indicative of its overall importance to model estimation of the dependent variable.

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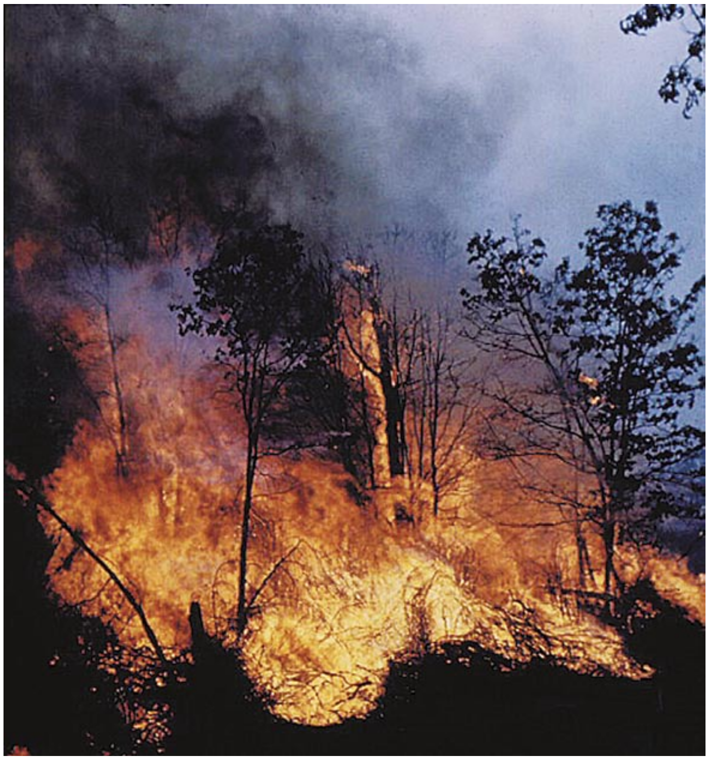

Wildfires appear to mobilize nutrients, which may then run off during rainfall. However, periodic burning helps to reduce nutrient levels in unnaturally heavy deposits of organic materials on the forest floor, thereby improving water quality in the long term.

burning, more-mosaic, prescribed fires (work in progress). Fuel reduction due to fire may cause an immediate increase in the surface mobility of nutrients, but the long-term effect may be a decrease in nutrient discharges due to the reduction in its source, the heavy surface deposits of decomposing organic litter.

Adaptive management implications

From an adaptive management standpoint, the question has been raised as to whether it is better to do nothing and risk a wildfire-induced "shock treatment" effect on nutrient discharge, or is it better to embark on a fuels reduction program (either mechanical or prescribed fire) with the ultimate objective of returning to a more natural fire regime characteristic of the pre–fire suppression era? We do not yet have the complete answer to this question, but are now beginning to understand the issues.

Fire suppression in forested watersheds has caused a decline in forest health (Johnson et al. 2005; Murphy et al. 2006; Neary et al. 1999) partially resulting in the heavy buildup of organic debris. This excess organic debris has apparently become a substantial source of biologically available nitrogen and phosphorus, which at least has the potential to move off-site into adjacent waterways (Loupe 2005). Doing nothing will certainly not help to alleviate the current problem of declining lake clarity. A wildfire clearly has the potential to cause an immediate adverse impact on discharge water quality. But the long-term effect of wildfires may be to improve water quality, because the lack of heavy surface deposits of decomposing organic materials after burning should ultimately reduce nutrient discharge concentrations over time. The best strategy is most likely some form of fuel reduction — such as mechanical harvest and/or prescribed fire — to lower the wildfire potential and at the same time reduce the current buildup and leaching of thick, nutrient rich, surface deposits of organic materials.

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RESEARCH ARTICLE

Erosion control reduces fine particles in runoff to Lake Tahoe

by Mark E. Grismer *and* A.L. Ellis

Sediment in hillslope runoff from disturbed soils in the Lake Tahoe Basin is the source of many fine suspended particles that transport nutrients and contribute to a loss in lake clarity. In previous studies, we used rainfall simulation to assess and quantify infiltration, runoff and erosion rates from hillslope soils. Building on this research, our current study evaluates the relationship between particle sizes in runoff sediments and slope, and compares the relationships between restored soil treatments and bare and undisturbed (native) forest soils. Soil restoration combined with pine needle mulch treatments substantially reduced sediment yields in runoff water, and increased the size of runoff particles when compared to that from bare soils. Very little, if any, runoff and erosion occurred from relatively undisturbed "native" soil plots at similar slopes.

A rainfall simulator was used to measure sediments in runoff under a variety of soil and groundcover conditions in the Lake Tahoe Basin.

Ever-increasing recreational use and housing development have increased the flow of sediments and nutrients into Lake Tahoe, decreasing its once-famous clarity by 30%, from approximately 100 to 69 feet (30 to 21 meters), over the last 3 decades. This loss of clarity and a tripling of algal primary productivity (growth) indicate the onset of lake eutrophication (Goldman et al. 1989; TRG 2002). Swift et al. (see page 49) have demonstrated the importance of 1 to 8 micron (μm) fine-sediment particles in diminishing the lake's clarity, both by transporting attached nutrients into the lake and scattering light when suspended in the water.

Road cuts and ski runs are important sources of damaging erosion and runoff in the Lake Tahoe Basin. Recently, regulators have increasingly focused on preventing runoff and retaining sediments within their original drainages (CTC 2001, 2004). The erosion-control treatments used at road cuts, ski runs and other sites in the basin can be broadly categorized, in order of decreasing runoff potential at a given slope, as: (1) bare soils (no treatment); (2) surface-treated soils, such as hydroseeded grasses, straw or mulch covers; (3) soil restoration treatments, such as tillage, the incorporation of woodchips, or compost combined with mulch covers; and (4) undisturbed "native" forest soils (Grismer and Hogan 2005b) (table 1). Unfortunately, several examples of erosion-control failures are visible in the semiarid, high-altitude environment of the Lake Tahoe Basin, especially along road cuts and ski runs.

Despite years of work, quantitative information has only recently been developed about the effectiveness of measures employed at road cuts and hillslopes to control erosion in the basin. In general, the literature related to erosion control involves agricultural activities and practices in relatively humid environments. There are few scientific field evaluations of erosion-control efforts involving revegetation and restoration in semiarid, subalpine environments such as the Lake Tahoe Basin. The information that is available on such environments is often limited to the "gray" literature of "white" papers from agencies or professional societies; these papers — while important — are not peer-reviewed or widely available, and so are not readily available for scientific scrutiny.

Nonetheless, erosion-control research and work are not new in the Tahoe Basin. For example, Maholland (2004) used geographic information system (GIS) assessment methods to determine that

Sediment yields were nearly 10 times greater from volcanic ski-run soils and both types of road-cut soils than from undisturbed (native) sites.

As expected, runoff from bare ground was greater than mulched and seeded plots, with a higher proportion of fine sediment particles.

TABLE 1. Estimated or known erosion-control treatment characteristics at Tahoe Basin rainfall simulation sites

Site*	Seed mix†	Amends‡	Fertilizer¶	Mulch Type	Depth	Tillage depth
					mm	*mm*
Granitic soils						
Bliss (RC)	None	Forest duff	None	Pine needle (PN)	25	150
Cave Rock (RC), Heavenly Mt. (SR)	Br ca, El el (100 kg/ha)	Compost	Biosol	PN over straw	50	150
Luther Pass — GV (RC)	El el, El gl, Br ca	Compost	Biosol	PN	25	None
Rubicon (RC)	Caltrans type-B grasses — planted	Compost	16-16-16	Straw and PN	~ 25	None
Volcanic soils						
Brockway (RC)	Various grass mixes (unknown)	Compost	Biosol	PN	10	100
Dollar Hill — west (RC)	Various bunchgrass mixes	None	Biosol	PN, hand-applied	30	None
Dollar Hill — east (RC)	Native grasses over std. mix w/yarrow	None	Biosol	Ground PN	50	None
Northstar Unit 7 (RC)	El el, El gl, Br ca	100 mm compost	Biosol	PN	25	300
Northstar (SRs) (Lookout Mt.)	Native and adapted grasses	None	Biosol	Straw	0	
Snowking (SR) (Juniper Mt.)	El el, El gl, Br ca	Compost and woodchips	Biosol	PN	25	300

* SR = ski run; RC = road cut.
† Various grass species: Br = Bromus, El = Elymus, ca = carinatus; el = elymoides; gl = glaucus. Caltrans type-B grasses include fescues.
‡ Forest duff = broken-down organic litter matter on forest floor (fine powder).
¶ Biosol is a proprietary soil amendment; 16-16-16 refers to the N-P-K content of the amendment.

forest roads and ski runs subject to hillslope rilling (small channels created by concentrated runoff) were the greatest sources of sediment in the mixed granitic and volcanic soils of the Squaw Creek watershed, northwest of Lake Tahoe.

Furthermore, White and Franks (1978) documented the near total destruction of benthic (stream bottom) communities from the excessive discharge of sediments following development of the Rubicon Properties on Lake Tahoe's west shore. Their important demonstration study of various erosion-control nettings at the Rubicon housing development and Northstar-at-Tahoe ski area was "largely ignored in the erosion-control literature" (Sutherland 1998). As a white paper, White and Frank's study was not circulated widely and the results were not incorporated in other studies. Yet while it lacked scientific rigor, this was a model study with rarely seen cooperation between agencies in attempting to limit erosion in the Tahoe Basin. Other studies relevant to erosion in the Tahoe Basin include those conducted in the basin by Fifield et al. (1988) and in semi-arid, alpine western Colorado by Fifield et al. (1989), Fifield and Malnor (1990) and Fifield (1992a, 1992b).

Standardized erosion evaluation

Rainfall simulations are a useful method for standardizing the evaluation of erosion-control measures. These studies entail replicated rainfall events of the same intensity (or kinetic energy) on multiple plots, enabling the statistical evaluation of erosion-control treatments on hydrologic parameters. Grismer and Hogan (2004, 2005a, 2005b) employed rainfall simulation on disturbed road cuts and ski runs with granitic and volcanic soils in the Tahoe Basin to evaluate how slope, groundcover and surface roughness (microtopography) affect infiltration and runoff rates, as well as sediment concentrations and yields in runoff.

Soil survey information is limited for the Tahoe Basin, but all the soils can be broadly grouped into granitic, volcanic or a mix of the two, with surface soil textures of cobbly or stony sandy loams. Grismer and Hogan (2004, 2005a, 2005b) determined that surface roughness and cross-slope (the slope diagonal to straight downslope) had no effect on sediment concentrations or yields in runoff under all treatments encountered. In addition, for nearly all groundcover conditions, volcanic soils had greater runoff rates, sediment concentrations and yields than granitic soils (Grismer and Hogan 2004).

In these studies, runoff rates and sediment yields from bare soils were significantly correlated with slope. Sediment yields from bare granitic soils at slopes of 28% to 78% ranged from about 1 to 12 grams per millimeter per square meter ($g/mm/m^2$) runoff, while sediment yields from bare volcanic soils at slopes of 22% to 61% ranged from about 3 to 31 $g/mm/m^2$ runoff (Grismer and Hogan 2005a). Furthermore, sediment yields were nearly 10 times greater from volcanic ski-run soils and both types of road-cut soils than from undisturbed (native) sites. Similarly, sediment yields were nearly four times greater from granitic ski-run soils than from native areas.

For both volcanic and granitic ski-run soils, revegetation or pine needle mulch decreased sediment concentrations and yields by 30% to 50%. Regardless of rainfall intensity, there was little or no runoff or sediment yield from either soil type after the soil was restored by either incorporating woodchips or tilling amendments such as Biosol or compost into the soil, or applying mulch covers (with or without plant seeding).

Sediment size in Lake Tahoe

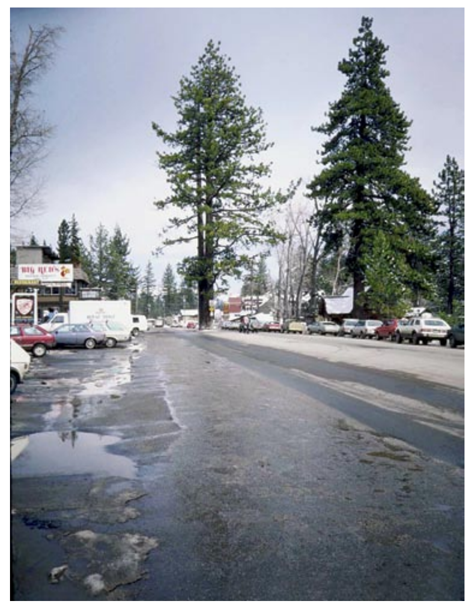
However, these previous studies did not analyze the particle-size distributions in runoff water, which is a critical component of Lake Tahoe's famed clarity and water quality. This paper reports on our study of the relationships between sediment concentration and yield, sediment yield and slope, and sediment particle size and slope for native (forest) and treated (at ski runs and road cuts) soils following rainfall simulation.

Battany and Grismer (2000) and Grismer and Hogan (2004) provide detailed descriptions of the rainfall simulation methodology that we used. The rainfall simulator consisted of a needle tank, tower assembly and associated plumbing hardware necessary to obtain steady rainfall intensity. Following a preliminary land survey of each site selected across the basin, several plots were established, the metal plot frame (31.5 inches by 31.5 inches [0.8 meter by 0.8 meter]) was installed, and the rainfall simulator was centered over the frame and leveled. Rainfall was allowed to continue until either steady runoff was obtained or about 60 minutes elapsed.

Following field measurements (including time to runoff, times of sample collection and surface topography), collected runoff samples were taken to the laboratory for filtration and analyses. Samples were vacuum-filtered first through a Whatman #541 filter and then through a 0.45 μm filter. Split samples were analyzed directly for particle-size distributions using the laser (Coulter) counting method (Eshel et al. 2004). The filter papers with sediment were dried at 105° C and then weighed, and total sediment mass per volume of runoff was determined. Sediment yield was determined as the slope of the linear regression (R^2 values ranged from 0.90 to 0.98) between cumulative sediment in the runoff and cumulative runoff. Steady sediment concentration in runoff was taken as the average of the last two-to-four individual sediment concentrations determined after runoff rates stabilized.

Several rainfall simulation tests were conducted during the summers of 2003 and 2004 on three soil types: volcanic, at Northstar (ski runs), Snowking (ski run) and Truckee highway interchanges (road cuts) on the north shore of Lake Tahoe; mixed, at a forest mastication test site near Tahoma on the west shore (see page 77); and granitic, at Heavenly Mountain Resort (ski run) and State Highway 89 (road cuts) on the south shore. At each site, rainfall simulation tests were conducted on three to six plots per treatment (bare, treated or native) and slope, depending on the relative consistency in measured val-

Phil Schermeister



Laurence R. Costello/UCCE San Francisco-San Mateo

Runoff from, *top*, ski areas and urban roads such as in, *above*, Tahoe City, are important sources of sediments that are having an adverse impact on the storied clarity of Lake Tahoe.

TABLE 2. Laser particle-size distribution measurements (means and standard deviations) for Tahoe Basin disturbed soils

Soil type	n	D_{10}	D_{30}	D_{60}	D_{90}	Sand	Silt	Clay
		. . . . . . μm				. . . . . . %		
Granitic mean	16	70.4*	294.8a	785.6a	1,589a	90.7a	7.82a	1.52a
Std. dev.	16	30.2	91.9	146.4	83.5	3.19	2.90	0.55
Volcanic mean	48	3.98b	41.3b	390.1b	1,227a	64.9b	28.2b	6.92b
Std. dev.	48	2.06	26.0	175.7	342.9	7.43	4.82	2.97
Tahoma mean	4	8.67b	66.0b	297.8b	1,194a	74.0c	21.8c	4.20ab
Std. dev.	4	3.06	6.39	54.2	245.6	2.11	1.45	0.85

* Mean values followed by different letters differ significantly ($P < 0.05$).

ues from plot to plot at similar slopes. Slope and soil type were taken as the independent variables, while sediment yield and particle-size fraction were the response variables as affected by plot treatment.

We characterized the particle-size distributions using the maximum size (D_{xx}), with xx corresponding to the percentage of particles less than that size. For example, the D_{50} particle size is the median, with 50% of the particles larger and 50% smaller; similarly, 10% of the soil particles are smaller than the D_{10} size. We considered particle sizes associated with less than 10%, 30%, 60% and 90% of the total sample (D_{10}, D_{30}, D_{60} and D_{90}, respectively). We then focused on the D_{30} size, since it is often used to estimate soil infiltration rates and also roughly corresponds to the less-than-8-μm particle size from the volcanic soils that are important to Lake Tahoe water clarity. Because we took measurements across a gradient (slope) and obvious differences resulted from soil type and treatment, we used regression analyses to develop possible causal relationships between slope and the response variables (sediment yield and particle-size fraction) (Cottingham et al. 2005).

Reducing fine sediments

Runoff and erosion rates from disturbed soils in the Tahoe Basin are primarily dependent first on soil type (granitic or volcanic), followed by the extent of soil restoration, and then slope and cover conditions (Grismer and Hogan 2004). While both soils are considered sand or sandy loam for any particular particle-size fraction, the average granitic particle sizes differed significantly (at 95% level using Tukey standardized range test) from and were several times larger than those of the volcanic soils (table 2). The Tahoma soils at the mastication site are mixed volcanic and granitic, and this was reflected in the particle-size fractions that we found, which fell between those two soil types. Perhaps more importantly, there were more 1-to-8-μm particles in volcanic soils than granitic. Furthermore, Grismer and Hogan (2005a) found that soil

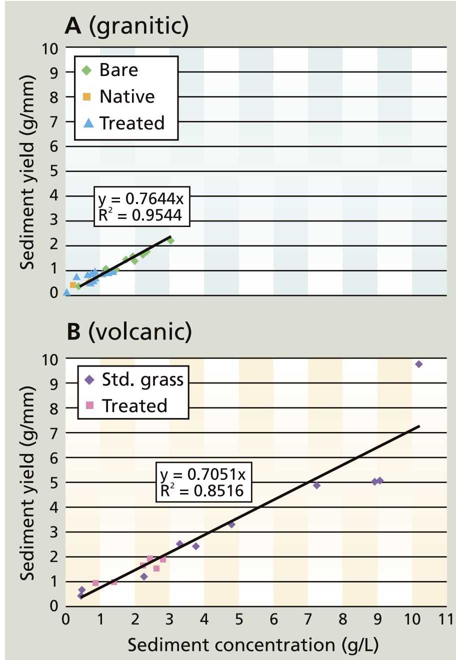


Fig. 1. Relationship between sediment yields and concentrations for all conditions from (A) granitic and (B) volcanic soils.

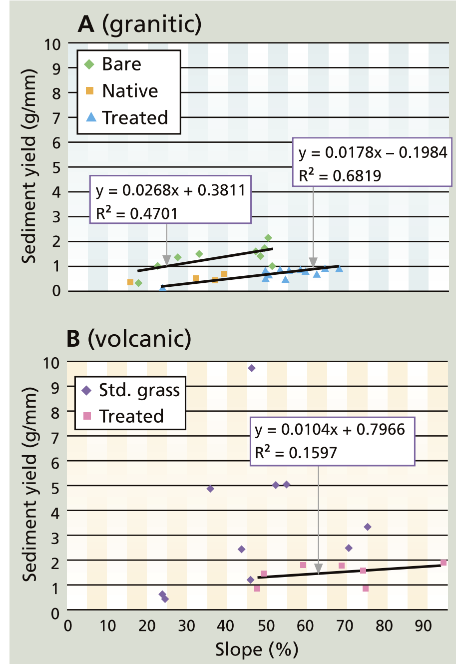


Fig. 2. Relationship between sediment yields and slope for all conditions from (A) granitic and (B) volcanic soils.

particle-size distributions tended toward the smaller sizes as slope increased in bare and treated disturbed soils.

To verify the consistency of using either sediment yield or sediment concentration to display our study results, we compared these two parameters for the two different soil types and all soil conditions (fig. 1). Not surprisingly, sediment yield was closely correlated with sediment concentration, particularly from bare soils (fig. 1A). However, the standard grass treatment was an annual grass (*Fescue* spp.) that provides 20% to 50% soil cover and does not include soil restoration (fig. 1B). In terms of runoff and erosion rates, this treatment was often similar to bare soils, although its ranges of cover caused greater variability in the relationship between sediment yield and concentration; nonetheless, it appears that these two parameters can be used interchangeably (table 3).

Generally, runoff and erosion rates (sediment yields) increased with increasing plot slope, since gravity helps soil to detach and flow downward. We found this to be true for the granitic soils in our study, but much less so for the volcanic soils; in some cases no runoff occurred from native volcanic soil plots even as slope increased (fig. 2). Furthermore, the range of sediment yields from the volcanic soils was on average four times greater than that from the granitic soils. For example, at slopes of 50% to 55%, sediment yields of about 5 grams per

TABLE 3. Statistics associated with regression relationships shown in figures 1, 2 and 3

Soil type	Soil treatment	n	Relationship*	R^2	F	*P* value
Granitic	All	25	SY vs. SC	0.954	477	< 0.0001
Volcanic	All	16	SY vs. SC	0.852	80.595	< 0.0001
Granitic	Bare	9	SY vs. slope	0.470	6.2075	0.04151
Granitic	Treated, native	16	SY vs. slope	0.682	30.025	< 0.0001
Volcanic	Treated	7	SY vs. slope	0.160	0.9524	0.37393
Granitic	Native	4	D_{30} vs. slope	0.979	93.238	0.01056
Granitic	Bare	9	D_{30} vs. slope	0.611	10.995	0.01284
Granitic	Treated	12	D_{30} vs. slope	0.321	4.7275	0.05477
Volcanic	Std. grass (*Fescue* sp.)	7	D_{30} vs. slope	0.312	2.2674	0.19246
Volcanic	Treated soil	10	D_{30} vs. slope	0.439	6.2603	0.03682

* SY = sediment yield; SC = sediment concentration; D_{30} Is the particle-size fraction larger than 30% of the total sample.

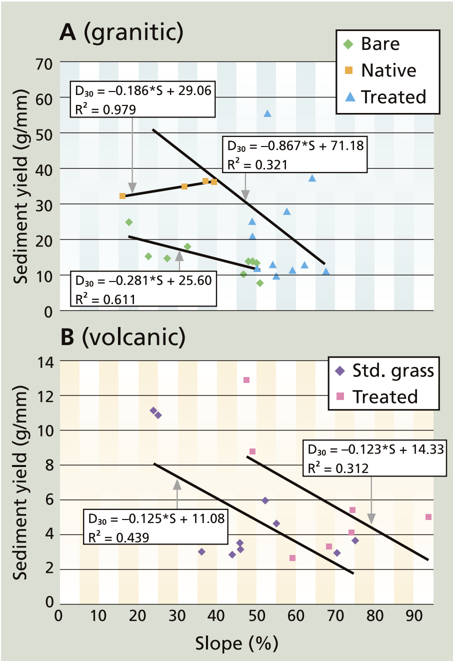


Fig. 3. Relationship between D_{30} particle-size fraction and slope for all conditions from (A) granitic and (B) volcanic soils. Y-axis scales differ by a factor of five between granitic and volcanic soils.

millimeter occurred from the standard grass-covered volcanic soils, roughly three times greater than that from bare granitic soils and nearly seven times greater than that from treated or native granitic soils. Soil treatments — either mulch and grass covers only or more complete soil restoration — significantly decreased runoff rates and sediment yields as compared to bare soils. However, for many of these plots, the original treatment specifications and date of treatment were not well known, thus the longer-term efficacy of these different treatments and erosion-control approaches is not known and is currently under investigation.

While sediment yield, or total sediment deposition, is an important factor in evaluating the efficacy of various revegetation and soil restoration efforts, the smaller particle size of less than 8 μm is potentially more critical, because it contributes suspended particles — possibly with attached nutrients such as nitrogen and phosphorus — into receiving water bodies. As observed by Grismer and Hogan (2005b), in our study particle sizes also tended to decrease with increasing plot slope for bare and treated soils regardless of soil type (fig. 3). Four of the five regression relationships were significant at the 95% level; however, given the limited results available for the native plots (where runoff rarely occurs), particle size in runoff did not appear to depend on plot slope. Clearly, this trend requires additional investigation; these studies are presently under way.

The D_{30} particle sizes in runoff samples from volcanic soils were generally less than about 8 μm for all conditions, while those from granitic soils generally exceeded about 10 μm (fig. 3). As with the decreased sediment yields associated with soil treatment, larger particle sizes were observed from the treated or restored soils as compared to bare or standard grass-cover soils of both soil types.

Effective erosion control

The degree to which runoff particle size can be increased by an erosion-control treatment has important implications for developing best management practices (BMPs) for disturbed soils at road cuts, ski runs and construction sites in the Tahoe Basin. The development of effective erosion-control strategies is critical to preserving water clarity in Lake Tahoe, meeting total maximum daily load (TMDL) goals, and improving overall water quality. We found that volcanic soils have smaller particle sizes than granitic soils, and that they release particle sizes in the 1-to-8-μm range of concern with respect to Lake Tahoe's clarity. Revegetation, mulch covers and soil restoration tended to increase infiltration, decrease sediment yields and increase particle sizes in runoff across a range of slopes. We are currently trying to verify these results further, to help local agencies with limited resources to focus erosion-control work on, for example, volcanic soils that may yield the greatest reduction in fine-particle delivery to the lake.

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RESEARCH ARTICLE

Mechanical mastication thins Lake Tahoe forest with few adverse impacts

by B. Hatchett, Michael P. Hogan
and Mark E. Grismer

An overstocked montane, mixed-conifer forest on the west shore of the Lake Tahoe Basin was thinned using a Fecon masticator, leaving woodchips and tree shreddings on-site as mulch. No significant differences in soil compaction were found in 13 of 15 comparisons of soil-profile resistance values at several distances from the machine track and varying depths. We then watered the mastication sites with a rainfall simulator, and measured runoff, infiltration and erosion. The treatments included woodchip-covered and bare-soil plots corresponding to mulched track, as well as native grass, bare soils and relatively undisturbed soil plots. Sediment yields were greatest from the bare soils, followed by the undisturbed, grass and woodchip plots. Mastication appears to be an effective thinning treatment for overstocked forests with few discernible negative impacts on soil compaction or lake-polluting runoff.

Mechanical mastication is a promising method for thinning overstocked forests. *Above*, a Fecon Bull Hog BH 80 masticator head is mounted to the boom of a Caterpillar 235 excavator.

Forest health, wildfire prevention and water-quality protection are interrelated environmental issues in the Lake Tahoe Basin and throughout the western United States. Overstocked forests are largely the result of fire suppression during the past 100 years by federal, state and private land-management agencies. Managers are now faced with forests of higher density and a high incidence of insect- and stress-related tree die-off, resulting in increased fire potential and disease transmissibility.

Fires in these overstocked stands tend to be high-intensity "scouring" fires, which leave little intact understory and sterilize the soil. Loss of cover leaves bare soils extremely prone to erosion, negatively affecting downstream water quality. To address these concerns, such forests are thinned by reducing standing biomass in the understory, reducing the density of timber stands, or both. A less common but promising method is employing a mechanical masticator to potentially address forest health, fire prevention and water quality. A mechanical masticator is similar to a wood chipper; it is mounted on an excavator-type crawler tractor, which moves through the forest to chip or shred trees and brush, leaving the woodchips behind. However, the environmental costs and benefits of treating forests with mechanical masticators have not been adequately studied.

Factors contributing to erosion

Considerable research has been conducted on the factors contributing to soil compaction and erosion in forest soils. Nolte and Fausey (1986) reported that if soil compaction (cone penetrometer resistance) doubles, water infiltration rates can decrease by a factor of ten. Wall et al. (1987) and Frisby and Pfost (1993) noted that decreased infiltration and increased runoff may result from compacted subsurface soil layers. Infiltration is a key variable in erosion because it regulates the amount of runoff entering the soil. The greater the relative infiltration, the lower the runoff rates and thus the lower potential erosion from a site (Radcliffe and Rasmussen 2000).

Imeson and Lavee (1998) examined the influence of temporal and spatial scales on erosion processes, and found that soil aggregate stability — the cohesive structure holding together individual soil particles — was a key indicator of erosion. Greater aggregate stability results in greater infiltration rates and increased resistance of aggregates to shear detachment, or breakup, thereby reducing erosion. Aggregate stability is controlled by the extent of shading (vegetation and litter coverage), organic matter dynamics (the turnover of organic matter, and root production) and slope angle and aspect (which direction it faces, such as north, south, etc.).

Plant cover is critical for controlling erosion. Trees and dense grasses can reduce erosion by 70% when compared to bare soil (Bonan 2002). Allred (1950) reported that rain-fed infiltration rates decreased drastically with reductions in vegetation cover and organic matter.

***Right and center,* the masticator grinds overstocked forest understory and leaves a layer of protective mulch. The authors evaluated whether the large machine's tread, *left,* contributes to soil compaction and subsequent runoff.**

Plant and litter cover protects the soil from raindrop impact and splash, tends to slow down the movement of surface runoff, and increases the infiltration rate and water-holding capacity of the soil (Wall et al. 1987; Molinar et al. 2001).

In forests, the factor used to estimate total erosion losses decreases from 0.36 on soils with no litter cover to 0.003 with 100% litter cover (Bonan 2002). Soils covered by vegetation or litter generally have high levels of aggregate stability, as do soils with favorable organic-matter contents. Litter cover also lowers the evapotranspiration rate from moist soils and reduces soil temperatures relative to bare soils, improving microbial soil habitats and enhancing grass-seed germination and establishment (Molinar et al. 2001). Slope angle is also important to both aggregate stability and erosion rates, depending on the aspect and initial stability of the soil. For example, on south-facing slopes, soils with low aggregate stability or low infiltration capacity tend to be more erosion prone than those on north-facing slopes, especially in the Sierra Nevada of California.

Benefits of forest thinning

Excess cover, however, especially in an overstocked forest, can create extreme fire danger and catastrophic results for the forest habitat and surrounding human habitation. Overstocked forest stands are thinned in numerous ways. Forest thinning involves removing small to medium-diameter trees and shrubs, which opens the canopy and forest floor and provides the remaining stand with access to more nutrients, sunlight, water and space. The thinned stand tends to grow with increased vigor and health, resulting in improved biodiversity of flora and fauna and better overall appearance. At the same time, less fuel is available for wildfires and the threat of crown fires is reduced. Open canopies also allow a greater accumulation of snow on the forest floor, leaving more water for both the ecosystem and human consumption upon melting (Bowling et al. 2000).

Methods of forest thinning include crews that hand-thin using chainsaws and then burn or chip the slash (branches and trimmings left after removing tree trunks for firewood), to mechanized thinning using heavy machinery such as the masticator. Burning may have the greatest implications environmentally and socioeconomically. Concentrated, intense heat from burn piles can sterilize nearby soil through the combustion of nutrients and organic matter. In addition, the generated smoke and ash reduce air and water quality, and result in local complaints about health and other quality-of-life issues. Furthermore, burn piles have the potential to become uncontrolled and result in large-scale wildfires, which occurred in the 2000 Cerro Grande Fire near the Los Alamos National Laboratory in New Mexico.

Soil compaction [after mastication] is not highly localized, but is dispersed over a large distance.

Mastication of fir tree stand

The purpose of our study was to determine if heavy mastication equipment used for stand-density reduction in an overstocked forest would increase soil compaction and, subsequently, runoff and erosion. The study site was on the west shore of Lake Tahoe near Tahoma and consisted of an overstocked, fir-dominated, second-growth forest on a soil derived from mixed granite and volcanic material common to the area. Soils at the site were mapped as Tallac-series gravelly coarse sandy loam (Inceptisol order as a loamy skeletal mixed Entic Cryumbrept) derived from glacial outwash deposits of basic and metamorphic rock (Rogers 1974). This soil series is moderately well drained with a weakly cemented silica layer at a depth of approximately 40 inches (1 meter). Tahoma is situated at the border between volcanic, primarily andesitic rock to the north and granitic rock to the south.

The study site is typical of many west shore forests logged more than 100 years ago (Wilson 1992; direct ring counting of cut trees in 2004). Subsequent to initial logging in the late 19th century of what was then a pine-dominated forest, red and especially white fir trees (*Abies magnifica* and *Abies concolor*, respectively) regrew first and became the dominant species. After the U.S. Forest Service acquired much of the land in the 1960s and 1970s, fires were routinely suppressed and logging was discontinued.

In the project area, white and red fir make up over 90% of the stand, with the remainder comprised of Jeffrey pine *(Pinus jeffreyi)* and incense cedar *(Calocedrus decurrens)*. Understory is relatively nonexistent in much of the area except where canopy openings occur; in these places there is a dense covering of golden chinquapin *(Chrysolepis sempervirens)*, whitethorn *(Ceanothus cordulatus)*

The study area in Tahoma, near Lake Tahoe, *left*, before and, *center*, after mastication treatment; *right*, the masticator grinds forest material into hand-sized chunks.

and greenleaf manzanita *(Arctostaphylos patula)* mixed with scattered forbs and grasses. Perhaps due to fire suppression, the forest floor was covered with at least 2 inches (5 centimeters) of needle litter, duff and other woody debris. In some areas, the mulch-duff layer was as much as 4 inches (10 centimeters).

Prior to treatment, the average actual stand density was as high as 2,020 stems per acre (5,043 stems per hectare) with an associated average canopy cover of 96.7%. Mean stem diameter at breast height (about 4 to 5 feet) was 5.7 inches (14.5 centimeters). (Following mastication treatment, the average stand density was 279 stems per acre [696 stems per hectare] or 13.8% of the original density; the associated average canopy cover after treatment was 25.7% but ranged from 6% to 31%.)

We thinned several acres of the study site with a Caterpillar 320C excavator equipped with low-ground-pressure (37.9 kPa or 5.5 psi) triple cleat grousers and a Fecon Bull Hog BH 80 masticator head. The use of low-ground-pressure machinery is believed to minimize short-term compaction and eliminate long-term impacts such as soil compaction and increased runoff.

The boom-mounted head was capable of reaching to approximately 30 feet (10 meters) laterally/horizontally and vertically from the excavator, so that the excavator did not get too close to individual trees. The Fecon masticator head utilizes a rotating cylinder with fixed cutting teeth that "chew" the forest material into mulch, which is then deposited on the forest floor. No burning is required for mastication, as all of the fuels are converted to small pieces, generally less than hand-sized, and left as a protective mulch layer.

However, the use of heavy machinery in the forest may result in soil compaction at the machine tracks and the establishment of an unintentional "trail" that lasts several years. In our study, mastication took place in October 2004; soils tend to be driest in the fall — with gravimetric moisture content less than 10% — resulting in less possible soil compaction. In addition, during mastication the operator was careful to minimize soil disturbance by steering the machine as straight as possible, with no pivot turns at any time and all turns made in as broad an arc as the terrain and surrounding timber allowed. Mastication also enables established tracks to be covered by mulched litter, thereby reducing bare-soil exposure and, in turn, erosion.

Measuring mastication impacts

Following mastication of the larger project area, we designated 12 rainfall simulation plots to determine infiltration and runoff rates located on three transect lines, along which soil compaction measurements were taken (fig. 1). The transect lines extended 50 feet (15.2 meters) perpendicular from the middle of the excavator track and were 20 feet (6.1 meters) apart, yielding a total study area of approximately 2,000 square feet (0.019 hectare).

Soil compaction. Measurements were taken in late June 2004, when sufficient soil moisture was present for an accurate test of potential compaction. A cone penetrometer was used to measure resistance to force in pressure units as an index of soil compaction. A Spectrum Fieldscout SC 900 soil cone penetrometer (0.5-inch diameter [1.3 centimeters] and 30° angle) with a data logger was used to measure resistance to a depth of 18 inches (46 centimeters). Recordings of the force required to insert the penetrometer in kPa (psi) were taken at 1-inch (2.5-centimeter) intervals at a maximum insertion rate of 1 inch (2.5 centimeters) per second. Soil strength was measured in each of five points located randomly along the excavator tracks.

Measurements were taken along each transect at 10-foot (3-meter) intervals, and at 10-foot (3-meter) intervals between transects along the machine track. Following Landsberg et al. (2003), we omitted all penetration values greater than five times the standard deviation of the mean resistance or greater than 3,400 kPa (500 psi) at a given depth for each respective transect, under the assumption that excessive pressure was used to penetrate rocks, root systems or thick organic matter decomposing below the surface.

Soil compaction is more directly measured through the collection of predetermined soil sample volumes that are dried and weighed in the laboratory. Unfortunately, this fixed-volume sampling method is very difficult, if not impossible, in loose soils. As such, soil bulk-density samples were not collected due to funding constraints as well as sampling problems experienced by Munn (1998) in a similar study conducted several miles south of our project area.

Ground coverage and density. We recorded field notes about each transect and

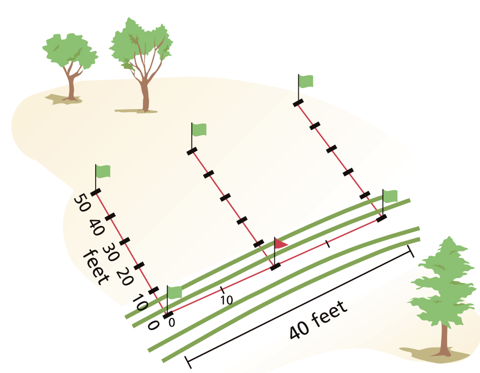


Fig. 1. Typical measurement plot and transect layout relative to excavator tracks (green lines).

TABLE 1. Mean and standard deviation of penetrometer resistance values (kPa) at distances from mastication track

Transect	Mean penetration depth (inches) 0	1	2	3	4	5	6	7	8	9
	kPa									
0	76.0	149.2	301.2	377.2	439.4	490.9	523.6	542.5	578.0	548.0
10 feet	16.1	48.8	168.1	260.2	368.9	436.6	385.0	461.0	469.3	482.7
20 feet	48.8	105.9	228.0	257.9	279.5	292.9	379.9	377.2	393.3	401.6
Std. deviations										
0	97.6	173.6	233.5	230.7	230.7	249.6	238.6	350.0	317.3	295.7
10 feet	21.7	48.8	140.9	168.1	265.7	341.7	206.3	265.7	350.0	341.7
20 feet	84.3	154.7	216.9	140.9	160.2	170.9	241.3	214.2	187.0	162.6

TABLE 2. Pairwise *t*-tests for penetrometer data*

Depth	Transect	*T*-value	df	*P*
2 inches	0–10 feet	0.6817	14	0.5065
	10–20 feet	−1.0236	14	0.3234
	0–20 feet	−0.2644	14	0.7953
4 inches	0–10 feet	0.5169	14	0.6133
	10–20 feet	1.0744	14	0.3008
	0–20 feet	**2.3218**	**14**	**0.0358**
6 inches	0–10 feet	1.5787	13	0.1384
	10–20 feet	−0.1172	11	0.9088
	0–20 feet	1.3864	11	0.1931
8 inches	0–10 feet	−0.2736	7	0.7923
	10–20 feet	0.3332	6	0.7503
	0–20 feet	1.7085	6	0.1384
10 inches	0–10 feet	0.7923	6	0.4583
	10–20 feet	0.3332	6	0.7503
	0–20 feet	**2.3446**	**8**	**0.0471**

* Significant differences at > 95% level in bold.

ocular estimates of the percentage bare ground on and off the mastication track. Overall stand density and changes in sky-view factor — the amount of sky visible through the canopy when viewed from the ground — were also noted using visual estimation following Bonham (1989).

Cover-point monitoring techniques (Elzinga et al. 1998) were used to determine the extent of exposed soil along overlaying transects (Crocker and Tivner 1948; Bonham 1989; Hogan 2003). Three 100-foot (30-meter) transects were surveyed, with five points sampled per transect for a total of 150 measurements each. Transects were surveyed in four areas: a track where mulching occurred, a track where no mulching occurred, a relatively undisturbed "native grass" area to acquire estimates of exposed soil in the tracks, and an undisturbed area.

Rainfall simulation. Following the cone penetrometer and cover-point monitoring measurements, a rainfall simulator was used to determine infiltration, runoff and erosion rates from bare, native grass and mulched track soils (Battany and Grismer 2000; Grismer and Hogan 2004). The 12 rainfall-simulator plots corresponded to the penetrometer measurement locations in the mulched track and were 10 to 20 feet (3 to 6 meters) from the tracks. Due to access constraints, we used the "midget" rainfall simulator, which has a 3-foot (1-meter) fall height (compared to 12 feet [3.5 meters] for the full-size rainfall simulator). Because the kinetic energy of rainfall generated by the midget rainfall simulator is approximately 30% less than that of the full-size rainfall simulator, a rainfall intensity of about 3 inches (73 millimeters) per hour was used, as compared to the 2.35 inches (60 millimeters) per hour used in previous studies (Grismer and Hogan 2004). On three of the plots, a rainfall intensity of 4.7 inches (120 millimeters) per hour was applied to determine if greater intensity would affect sediment concentrations and yields.

Prior to rainfall simulation, a hand-held moisture meter (a time domain reflectometry [TDR] probe) was used to measure pre-rainfall soil moisture at several locations in each plot. Rainfall was allowed to continue until either steady runoff was obtained or about 30 minutes had elapsed. Following field measurements, collected runoff samples were taken to the laboratory for filtration to determine sediment and organic matter content (Eshel et al. 2004).

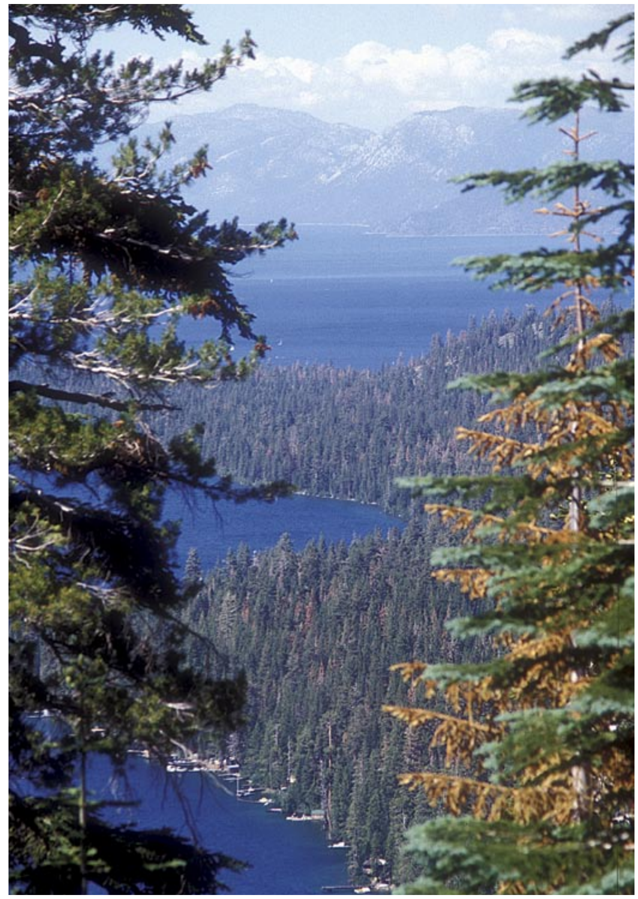
Little impact on soil compaction

The penetrometer data was statistically evaluated using a paired *t*-test to compare resistance measurements for varying distances from the track at similar depths. The null hypothesis was that there would be no difference in penetration resistance for a given depth at varying distances from the track. The null hypothesis was rejected at *t* values greater than absolute-value 2.00 and $P < 0.05$ (95% confidence) (tables 1 and 2). Depths of 0 and 1 inch (2.5 centimeters) were not analyzed because surface depth measurements were inconsistent due to instrumentation uncertainties; although these inconsistencies were much less prevalent at the 1-inch (2.5-centimeter) depth, they did still occur with enough frequency to render the data unreliable. Penetration resistance increased with depth, and values were 58% greater at the 4-inch (10-centimeter) depth than at the 2-inch (5-centimeter) depth across all measurements. At a given depth, penetration resistance generally declined as distance from the track increased.

No exposed soil was found in the tracks where mulching occurred. Where no mulching occurred in tracks there was 9% bare soil compared to approximately 6% in a nearby native grass area. As expected, the estimated overall forest-stand density was visibly lower, while the sky-view factor was greater in the masticated area when compared to an adjacent untreated area.

Results from the cone penetrometer measurements suggested that the use of heavy mastication machinery did not result in significant compaction at most soil depths, regardless of the distance from the machine tracks. At the 4-inch (10-centimeter) depth, the significant increases in soil strength that occurred were likely due to the machine travel. Reasons for the significantly increased compaction at the 10-inch (25-centimeter) depth are not clear. However, it is likely that the change in textural and organic content associated with a typical Tallac series soil, where organic carbon falls from 4.85% to only 2.17% below about 5 inches (13 centimeters), may play a key role since higher organic carbon content is associated with a greater propensity toward soil deformation or less resistance.

Assuming that machine use increases overall soil compaction, we would expect a trend of increased compaction across all depths of the soil at all distances from the track. However, no significant increases in compaction were found between the machine track and the 10-foot (3-meter) distance; the only significant increases were between the machine track and the 20-foot (6.1-meter) distance. This suggests that any compaction due to machine use is detectable only when comparing soil strength in the actual path of the machine to much-less-disturbed soil distant from any machine travel. That is, soil compaction appears not to be highly localized but rather is



Above, **runoff from masticated sites with granitic soils were much more likely to contain certain sizes of sediment particles than those from volcanic soils.** ***Right***, **forests in the Tahoe Basin are severely compromised by the suppression of wildfires, disease and insect stress.**

dispersed gradually over a large distance so that significant increases occur only when extreme distances are compared.

Rainfall doesn't increase erosion

Results from the rainfall simulator tests indicated that regardless of the surface treatment, erosion and runoff rates depended largely on whether the soils were of granitic or volcanic origin. This observation was supported by particle-size analyses of bulk soil samples collected from the project site. We characterized the particle-size distributions using the maximum size (D_{xx}), corresponding to the percentage of particles less than that size. For example, the D_{50} particle size is the median, with 50% of the particles larger and 50% smaller; similarly, 10% of the soil particles are smaller than the D_{10} size. D_{10}, D_{30} and D_{60} particle sizes are often used in geotechnical engineering studies to estimate infiltration rates. Generally, the larger the particles in a soil, the greater the infiltration rates.

We found that the mean D_{10}, D_{30} and D_{60} particle sizes of granitic soils in the Tahoe Basin were approximately twice those of the volcanics (table 3). As expected from the site description, soil particle sizes from the masticator treatment site fell between those from other granitic and volcanic soils, although they were more similar to other granitic soils in the basin (Grismer and Hogan 2005). Thus, we expected infiltration rates at the site to be somewhat less than that from other granitic soil sites, but much greater than that from volcanic soils sites.

Also as expected, sediment yields were greatest from the bare soil plots, although one of the bare plots had unusually deep soil and did not generate any runoff. Slope angles were quite similar between different treatment plot averages (table 4). No runoff was generated from any of the native grass or woodchip-covered plots, or from the undisturbed (native) plots at the normal rainfall rate of 2.9 inches per hour (73 millimeters per hour). This result suggests that for rainfall events as high as three times the 20-year, 1-hour storm sometimes used to design stormwater runoff structures in the basin, there is no runoff from woodchip-mulched mastication sites with slopes of up to about 20%. Higher-intensity rainfall (4.7 inches or 120 millimeters per hour) did generate runoff from these plots, resulting in sediment yields from the woodchip, grass cover and native plots that were 32%, 24% and 9.5%, respectively, of that from the bare soil. Not surprisingly, organic matter fractions were about 60% greater in the runoff sediment trapped on the filters in the lab (rather than soil minerals) in the woodchip, grass cover and native soil plots than in that from the bare soils. It should be noted that such high-intensity (4.7 inches per hour) rain events of 15-minute durations are extremely rare in the Tahoe Basin.

Particle-size distributions in the runoff samples collected during the rainfall simulations from all plots were similar to those from other granitic soils, consistent with the particle-size measurements of the bulk soil samples collected (table 5). Runoff particle sizes from the woodchip plots were much larger than those from the bare, native and grass cover soils, suggesting that masticated woodchips may be an effective control for the small par-

TABLE 3. Particle-size distribution measurements for disturbed granitic and volcanic soils in the Tahoe Basin (size fractions)

Soils	n	D_{10}	D_{30}	D_{60}	D_{90}
Granitic		.... μm			
Mean	33	117.06	322.48	946.36	ND
Std. deviation (CV %)	33	20.4 (17.4)	73.9 (22.9)	208 (22.0)	ND
Volcanic					
Mean	28	4.62	16.37	37.68	68.64
Std. deviation (CV %)	28	0.99 (21.5)	2.63 (16.1)	5.83 (15.4)	9.31 (13.6)

TABLE 4: Averages of measured parameters from rainfall-simulator plots on Tahoma masticator site soils

Treatment	Slopes Down	Slopes Cross	Time to runoff	Cumulative value @ 15 min. Runoff	Cumulative value @ 15 min. Sed.	Steady Infiltration	Steady Runoff	Steady S. conc.	OM	Sed. yield	R^2
	······ % ······		*sec*	*mm*	*g*	*mm/hr*	······· *g/L* ·······		*%*	*g/mm*	*%*
Normal (2.9 in/hr)											
Bare soil	16.47	12.43	369	0.70	1.12	59.77	13.23	0.91	14.3	1.48	89.49
Woodchips	19.05	12.13	No runoff								
Grass cover	13.49	7.20	No runoff								
Native (undisturbed)	15.48	9.43	No runoff								
High-intensity (4.7 in/hr)											
Woodchips	23.42	13.60	364	1.84	0.91	103.55	16.45	0.76	23.14	0.48	97.92
Grass cover	17.07	8.41	125	6.48	1.97	87.23	32.77	0.24	21.50	0.36	84.14
Native (undisturbed)	15.48	9.61	136	2.80	0.28	111.84	12.41	0.04	24.28	0.14	79.05

TABLE 5. Particle-size distributions in runoff samples from rainfall-simulator masticator plots in the Tahoe Basin

Treatment	D_{10}	D_{30}	D_{50}	D_{60}	D_{90}
	·········	·········	*µm*	·········	·········
Bare	11.68	42.90	114.97	189.42	881.43
Grass	11.40	39.07	78.47	116.93	666.00
Native	10.77	32.07	73.77	123.67	713.00
Woodchips	15.35	57.80	162.50	289.50	1,283.00

ticles that are associated with declining water clarity in Lake Tahoe (see page 49).

As observed elsewhere in the basin, native grass cover and the incorporation of woodchips dramatically reduce sediment loss. Rainfall simulations at this site were taken less than one season after mastication; additional assessments will be useful and are anticipated. In areas like our study site, where topsoil remains and is only slightly disturbed, impacts 1 to 3 years later may be quite different than during the first season following mastication treatment.

Benefits of mastication

Our results suggest that erosion is slight to insignificant following mastication, provided that a layer of woodchip mulch is left on the forest floor and the mastication equipment is operated in an environmentally effective manner. The resulting thickly mulched litter layer may offset any increased erosion potential that results from the limited soil compaction that may occur. In addition, any decrease in the potential for root growth due to compaction should be offset by the renewed vigor of growth in the stand due to thinning. Indeed, the combination of a mulched layer and thinning has the potential to decrease erosion and increase overall stand health.

While some have suggested that mastication has a high potential for ground compaction and increased erosion, our study clearly showed that this is the case only when bare ground is present. From a watershed perspective, sediment moving from bare areas is likely to be captured in more heavily mulched areas. However, our study only considered conditions at the site one winter season following mastication; long-term impacts are unknown.

Ultimately, the decision to use specific practices for improving forest health will depend on social, economic and environmental factors. Our results suggest that mastication may be a more time- and cost-effective method of forest thinning. Considering its relatively low or nonexistent environmental impacts, properly implemented mastication offers a potentially useful tool to achieve forest and watershed health goals.

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RESEARCH ARTICLE

Yellow starthistle continues its spread in California

by Michael J. Pitcairn, Steve Schoenig, Rosie Yacoub *and* John Gendron

Yellow starthistle is an exotic invasive weed that is estimated to infest over 14 million acres in California and is considered the most common exotic weed statewide. We reviewed several previous studies and conducted a township survey to provide an up-to-date analysis of the weed's rapid spread throughout the state. A county-by-county comparison between 1985 and 2002 showed increases in yellow starthistle in all regions of the state except for northeast California and the southeast desert region. Currently, most infestations occur in Northern California, but future invasions and spread will likely occur in the coastal counties of Southern California.

Baldo Villegas/CDFA

Yellow starthistle is the fastest-moving and most-widespread invasive, nonnative plant in California history. Dale Woods of the California Department of Food and Agriculture and Bill Bruckart of the U.S. Department of Agriculture examine the weed in Placer County.

Yellow starthistle is an exotic, noxious weed commonly found in rangelands and along roadsides and walking trails throughout California. Approximately 1-inch-long spines extend from the flower heads in a star-like pattern, giving rise to its common name of "starthistle." These spines are a bane to hikers and discourage feeding by grazing animals. Although not toxic to most animals, yellow starthistle (*Centaurea solstitialis* L. [Asteraceae]) is poisonous to horses and can cause brain lesions that may eventually kill them (Cordy 1978). Yellow starthistle favors disturbed soils but is also capable of invading undisturbed areas. Once this weed gains a foothold, it can build up dense populations that displace native and other desirable vegetation. Yellow starthistle is native to the Mediterranean climates of southern Europe and northern Africa and was first recorded in California near Oakland (Alameda County) in 1869. It is now considered the most common weed in the state.

Yellow starthistle was likely introduced many times to California as a contaminant of alfalfa seed (DiTomaso and Gerlach 2000). In the late 1800s, alfalfa seed from Europe, Asia and South America was imported for planting in the Sacramento Valley, and early records show that yellow starthistle was a frequent contaminant in these shipments. By 1917, this weed was common along roads, trails, ditches and railroad tracks throughout the Sacramento Valley (DiTomaso and Gerlach 2000). Yellow starthistle's primary means of spread is through human activity. The weed's seed can be transported over long distances by automobiles and earth-moving equipment, and in contaminated soil, crop seed and hay. More locally, the seed can be carried on animal fur and hiking boots and clothing, and by moving water. Wind does not appear to be an effective dispersal method.

Previous infestation estimates

Since the late 1950s, three estimates of the number of acres infested by yellow starthistle in California have been undertaken (Maddox and Mayfield 1985). The first, by the California Department of Food and Agriculture (CDFA), used responses from a questionnaire sent to county agricultural commissioners in 1958; the infested acreage of yellow starthistle was estimated at approximately 1.2 million acres (486,000 hectares). A similar survey undertaken by CDFA in 1965 found an estimated 1.9 million infested acres (769,000 hectares).

Donald Maddox and Aubrey Mayfield performed the third estimate 20 years later, in 1985. They also distributed questionnaires to the county agricultural commissioners but included UC Cooperative Extension farm advisors and other interested parties as well. Maddox and Mayfield estimated the number of acres infested with yellow starthistle at approximately 7.9 million acres (3.2 million hectares), a four-fold increase from 1965.

Unlike the previous two surveys, Maddox and Mayfield (1985) also reported the infested acreage by county and identified those with high and low infestation levels. High infestation counties had at least 1,000 acres (405 hectares) of yellow starthistle. In 1985, 38 of California's 58 coun-

Baldo Villegas/CDFA

A native plant of southern Europe and northern Africa, yellow starthistle was first recorded in California near Oakland in 1869.

Starthistle abundance guidelines

The following descriptions were provided to cooperators in the township survey to provide guidance in scoring yellow starthistle abundance.

Low:

- Only a single plant was found in the township.
- The only plants found were scattered plants and confined to the roadsides.
- Plants were scattered throughout the township, but did not occur in high densities.
- No dense patches or a few small, dense patches (< 10 acres) were observed.

High:

- Plants occurred primarily along roadsides, and quite dense for several miles.
- Plants not confined to roadsides, but observed throughout neighboring fields.
- Dense patches of plants > 10 acres found in at least three sections.
- Everywhere you looked you saw yellow starthistle plants.

ties had high infestation levels, with Lake County the highest, followed by Siskiyou, Humboldt and Trinity counties. Six counties reported no infestations: Alpine, Imperial, Inyo, Mono, Orange and San Francisco. In addition, Maddox and Mayfield grouped the county estimates into seven regions that represented the state's major drainage areas. The Sacramento and North Coast drainages had the highest infestation acreage, representing over 76% of the total reported acreage of yellow starthistle for the state.

Maddox and Mayfield's survey showed that the invasion and spread of yellow starthistle in California differed regionally. Northern California had more areas with high infestation levels and Southern California had fewer invaded areas, especially in the South Coast and San Joaquin drainages. This difference was attributed to the Northern California infestations having been in place longer than those in Southern California. Other regions with low infestation levels, such as the higher elevations of the Sierra Nevada and the Sonora and Mojave deserts, were believed to have climates that limit population growth and resist invasion by yellow starthistle.

Knowing the distribution of an invasive weed is of direct importance to its management. If an uninfested area is climatically unsuitable for yellow starthistle, then control efforts may not be necessary. However, if an area susceptible to yellow starthistle has not yet been infested, it might be feasible to control this noxious weed before it becomes abundant and impractical to manage. Studies have shown that controlling exotic weeds at the early stages of invasion is the most successful and cost-effective strategy (Randall 1996; Rejmanek and Pitcairn 2002).

Planning and prioritizing control measures at the regional level requires detailed knowledge of the target weed's distribution. For example, the U.S. Department of Agriculture and CDFA are implementing a statewide distribution effort of several biological control insects for yellow starthistle. For this effort to be successful, it is critical to know where yellow starthistle occurs so that all infestations are targeted for releases (Villegas 2001a, 2001b; Woods and Villegas 2005).

Surveying occurrence by township

To provide a more detailed and more recent assessment of the spread of yellow

Joe DiTomaso

Human activity, such as the use of automobiles and agricultural equipment, is the primary means of dispersal for yellow starthistle seeds. While nontoxic to most animals, it causes neurological diseases in horses. High densities crowd out native vegetation, discourage grazing and annoy hikers.

starthistle statewide, we performed a survey of its occurrence by township. A legal township in the Federal Public Lands Survey is a 6-mile-by-6-mile square (9.6-kilometers-by-9.6-kilometers). Early land surveyors throughout much of California established townships in the late 1800s. We purchased county maps and used markers to highlight the grid of township borders printed on them. For areas where townships were not established, such as many of the early Spanish land grants, we used markers to extend the grid into those areas.

These marked-up county maps were distributed to CDFA's Weed and Vertebrate Program biologists, who coordinate the eradication of noxious weeds throughout the state. We asked that each township be given a score of "0" for no yellow starthistle plants, "1" for low abundance and "2" for high abundance. Guidelines were provided as to what constituted low and high abundance (see box, page 84). Some program biologists completed the maps themselves, while others distributed them to the county agricultural commissioners in their districts. The township grid survey was performed in 1996 and 1997. All information collected during the survey was transferred into a geographic information system (GIS) database and a preliminary map of yellow starthistle in California was produced (Pitcairn et al. 1998).

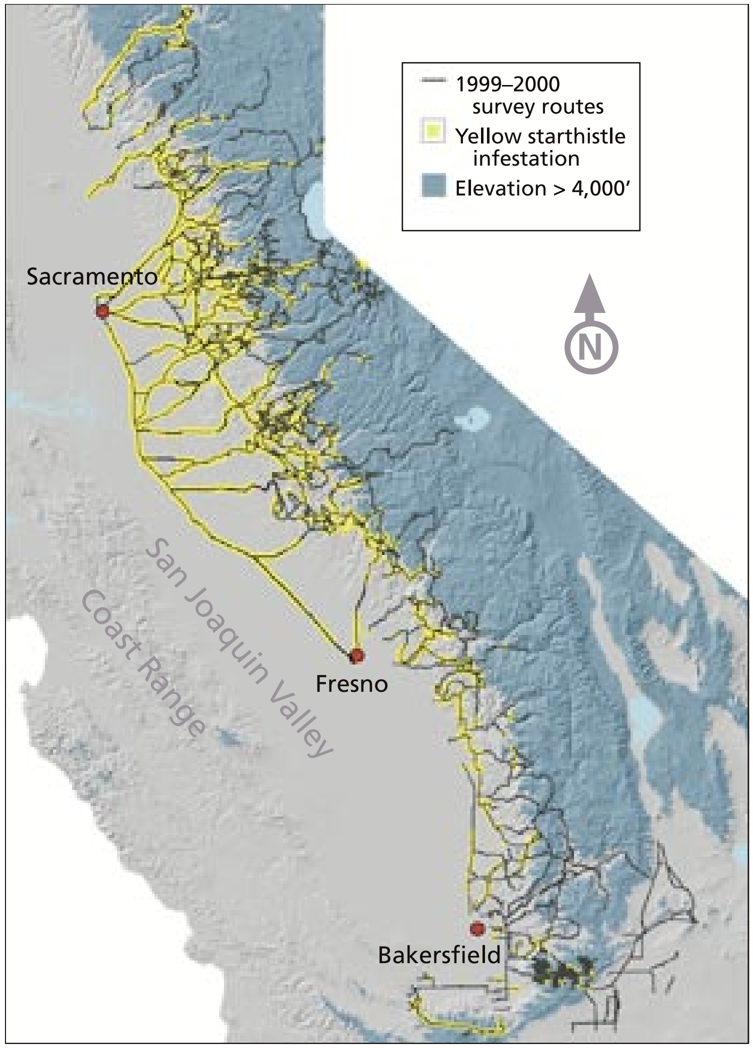

Fig. 1. Surveys of roads in the Sierra Nevada in 1999 and 2000 showed yellow starthistle to be less common at elevations above 4,000 feet (1,220 meters).

Sierra Nevada and Kern County. In compiling the township grid data, we learned that knowledge of the occurrence of yellow starthistle was particularly weak or missing in the mid-elevations of the Sierra Nevada and throughout Kern County. Both areas are important transitions from the Central Valley to the mountains in the east and the desert in the southeast, respectively. Before a final map of yellow starthistle in California was produced, we examined these two areas more closely. Information on the occurrence of yellow starthistle in Kern County was provided by the agricultural commissioner's office, which performed a local noxious weed survey in 2000.

In cooperation with the California Department of Transportation, in 1999 we surveyed for yellow starthistle along 14 major roads crossing the Sierra Nevada as well as along many of the smaller roads in between them. The objective was to identify how far yellow starthistle had spread into the higher elevations. If control efforts were focused on local eradication of new, incipient populations, large tracts of important public and private land might be protected from invasion. In addition, the infested acreage along the advancing front of the invasion might be relatively small and control costs low, especially compared to the value of the area to be protected.

The survey was broken into three phases: a general survey of the highway roadsides, a survey of areas beyond the right-of-way to determine how far yellow starthistle extended away from the roadside, and a resurvey of the upper elevations to determine if plants that germinated later in the season were missed during the survey's first phase. Surveyors used global positioning systems (GPS) to mark yellow starthistle locations, and all data were entered into a GIS database.

In 2000, we coordinated a survey over the same geographic area, taking advantage of the recently formed Weed Management Areas to acquire contacts from many different private and public landowners throughout the region. Weed Management Areas are local coalitions of public and private landowners that work on invasive weeds. They typically include representatives from state and federal agencies with land in the area, land managers from local park districts, large private landowners and concerned citizens. We incorporated

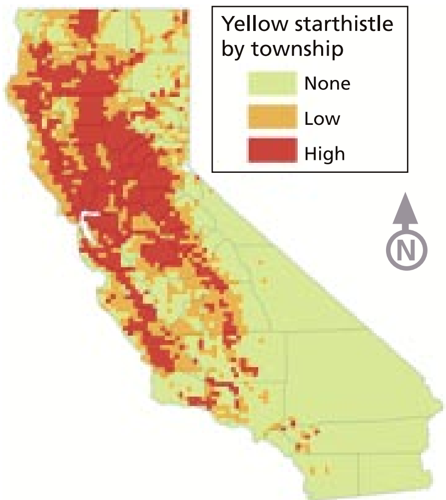

Fig. 2. Occurrence of yellow starthistle by township, incorporating information from all surveys through 2002.

into our database any information on areas surveyed for yellow starthistle or incidental finds collected by cooperators. This included GPS positions, GIS-digitized locations, road descriptions and paper maps. Additionally, we resurveyed some of the highways that were surveyed in 1999 and many of the smaller mountain roads, again using GPS units to record locations.

The results of these two road surveys showed an edge to the spread of yellow starthistle into the Sierra Nevada (fig. 1). When mapped with elevation contours, yellow starthistle was generally not common above elevations of 4,000 feet (1,220 meters). While major highways in the northern Sierra Nevada (such as Interstate 5 and Highway 50) had infestations well above this elevation, yellow starthistle was much less frequent or absent above 4,000 feet (1,220 meters) in the central and southern portion of the mountain range. In addition, while yellow starthistle was common along some roads in the Tehachapi mountains, almost none was observed on the eastern side of mountains in the Mojave Desert.

Modoc County, statewide surveys. Two more yellow starthistle surveys also became available and were incorporated into our township grid database. First, Modoc County performed a noxious weed survey in 2002, and this information was used to update the township grid data they

TABLE 1. Yellow starthistle infestation totals reported by county agricultural commissioners, 2002

County	Total county acres*	1985 gross†	2002 gross	Increase	Portion county infested	2002 net	Net/gross ratio
		· · · · · · · acres · · · · · · ·		%	%	acres	% cover
Alameda	528,270	20,000	200,000	900	38	15,000	7.5
Alpine	465,030	0	250	—	< 1	11	4.4
Amador	384,810	243,000	243,000	0	63	33,000	13.6
Butte	1,065,490	463,000	463,000	0	43	50,000	10.8
Calaveras	663,290	100,000	400,000	300	60	150,000	37.5
Colusa	739,740	246,000	265,000	8	36	50,000	18.9
Contra Costa	510,680	470,400	310,000	–34	61	44,000	14.2
Del Norte	641,920	4	1,000	24,900	< 1	1	0.1
El Dorado	1,155,040	5,000	650,000	12,900	56	129,000	19.8
Fresno	3,838,820	3,000	925,000	30,733	24	303,000	32.8
Glenn	844,160	10,000	400,000	3,900	47	175,000	43.8
Humboldt	2,303,690	686,000	250,000	–64	11	50,000	20.0
Imperial	2,942,340	0	0	0	0	0	0.0
Inyo	6,462,640	0	10	—	< 1	2	20.0
Kern	5,229,000	100	4,500	4,400	< 1	2,500	55.6
Kings	918,790	10	120	1,100	< 1	100	83.3
Lake	848,960	800,000	500,000	–38	59	176,000	35.2
Lassen	3,001,780	500	1,000	100	< 1	500	50.0
Los Angeles	2,610,730	2	415	20,650	< 1	125	30.1
Madera	1,374,160	300	10,000	3,233	< 1	5,000	50.0
Marin	376,300	2,000	2,200	10	< 1	1,500	68.2
Mariposa	938,690	200,000	250,000	25	27	200,000	80.0
Mendocino	2,246,840	250,000	1,000,000	300	45	400,000	40.0
Merced	1,284,930	1,000	600,000	59,900	47	120,000	20.0
Modoc	2,777,870	120	500	317	< 1	210	42.0
Mono	1,985,950	0	1	—	< 1	1	100.0
Monterey	2,127,430	6,000	1,650,000	27,400	78	56,000	3.4
Napa	510,010	242,560	242,560	0	48	85,120	35.1
Nevada	635,010	200,000	248,000	24	39	75,000	30.2
Orange	502,440	0	0	0	0	0	0.0
Placer	964,140	274,000	360,000	31	37	145,000	40.3
Plumas	1,675,780	800	13,000	1,525	< 1	3,300	25.4
Riverside	4,635,540	251+	2,080	729	< 1	920	44.2
Sacramento	649,780	320,000	320,000	0	49	25,000	7.8
San Benito	894,150	72,000	80,000	11	9	8,000	10.0
San Bernardino	12,905,960	2,890	1,500	–48	< 1	58	3.9
San Diego	2,739,560	15	26	73	< 1	8	30.8
San Francisco	58,300	0	1,000	—	2	12	1.2
San Joaquin‡	919,180	72,000	333,143	363	36	38,883	11.7
San Luis Obispo	2,128,800	10,000	60,000	500	3	15,000	25.0
San Mateo§¶	339,690	27	5,000	18,419	1	5,000	100.0
Santa Barbara	1,756,580	3,000	5,720	91	< 1	3,000	52.4
Santa Clara	842,160	5,000	7,307	46	< 1	7,040	96.3
Santa Cruz	281,360	75	250	233	< 1	100	40.0
Shasta	2,464,140	400,000+	500,000	25	20	333,000	66.6
Sierra	613,500	5	364	7,180	< 1	73	20.1
Siskiyou	4,043,710	768,000	1,010,000	32	25	252,500	25.0
Solano#	558,210	20,000+	95,794	379	17	24,906	26.0
Sonoma	1,022,460	100,000	100,000	0	10	10,000	10.0
Stanislaus	973,580	227,000	227,000	0	23	45,050	19.8
Sutter	388,480	200,000	199,324	0	51	65,450	32.8
Tehama	1,904,640	40,000	789,267	1,873	41	137,934	17.5
Trinity	2,062,500	612,672	200,000	–67	10	50,000	25.0
Tulare	3,100,710	10,000	20,000	100	< 1	6,000	30.0
Tuolumne§	1,467,320	212,818	40,000	–81	3	40,000	100.0
Ventura	1,192,680	5	250,000	4,999,900	21	100,000	40.0
Yolo	661,760	198,600	660,760	233	100	165,440	25.0
Yuba	409,020	407,680	407,680	0	100	80,000	19.6
Total	101,563,500	7,905,834	14,305,771	81	14	3,682,744	25.7

* Source: Hornbeck et al. 1983.
† Source: Maddox and Mayfield 1985.
‡ No estimate submitted; gross and net values were estimated as the average of values reported by Sacramento and Stanislaus counties.
§ Only net acreage provided.
¶ Value provided by San Mateo Weed Management Area.
# Only gross acreage provided; net acreage was estimated as 26% of gross acreage (based on the average ratio between total net and gross acreage for the other counties reporting both values).

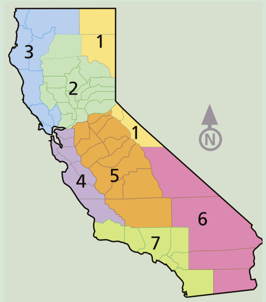

TABLE 2. Comparison of yellow starthistle infestations for major California drainage areas, 1985 and 2002

	Gross acreage		% of total		Net acreage		Net/gross
Drainage area	1985*	2002	1985	2002	2002	% of total	ratio
1. Northeast interior basins	58,219	1,751	0.7	< 0.1	722	< 0.1	41.2
2. Sacramento drainage	3,235,035	5,872,189	40.9	41.0	1,635,103	44.4	27.8
3. North Coast drainage	2,792,186	2,805,760	35.3	19.6	849,121	23.1	30.3
4. Central Coast drainage	355,042	2,313,557	4.5	16.2	150,152	4.1	6.5
5. San Joaquin drainage	1,458,300	3,052,763	18.4	21.3	943,533	25.6	30.9
6. Southeast desert basins	2,796	10	< 0.1	< 0.1	2	< 0.1	20.0
7. South Coast drainage	4,256	259,741	< 0.1	1.8	104,111	2.8	40.1
Total	7,907,819	14,305,771	100.0	100.0	3,682,744	100.0	

*Source: Maddox and Mayfield 1985.

had submitted in 1997. Second, CDFA conducted a statewide survey in 2001 and 2002 of biological control agents released against yellow starthistle (Pitcairn et al. 2003). This survey consisted of collecting yellow starthistle plants from 421 locations throughout California and examining them for the presence of four insects known to attack the seed heads. We overlaid the yellow starthistle collection locations on the township map, and then updated the map accordingly.

Final map. The information from all surveys through 2002 was compiled into a final map of yellow starthistle occurrence by township (fig. 2). Of the 6,389 townships statewide, 3,010 had yellow starthistle (1,441 had low abundance and 1,569 had high abundance). These infested townships account for approximately 47% of the surface area of California. The high-abundance townships occurred primarily in the Sacramento Valley and Sierra Nevada foothills, but were also reported for several coastal valleys from San Luis Obispo County to Humboldt County. The northeast interior and desert basins had few infestations of yellow starthistle.

Number of infested acres

The township grid map provides our best estimate of the extent to which yellow starthistle has spread, but provides no information on the amount of actual acres infested. To address this question, in 2002 we repeated the questionnaire survey of infested acres performed by Maddox and Mayfield (1985). In contrast to the previous three questionnaires, we requested two estimates of yellow starthistle infestations: gross acreage and net acreage. Gross acreage is the amount of land over which yellow starthistle populations are distributed. This is how the acreage of plant infestations is usually estimated, and how the results from the previous three surveys were reported.

Net acreage is the amount of land actually covered by the yellow starthistle plant canopy. For example, if one 10-acre (4-hectare) plot had 100 yellow starthistle plants while another 10-acre plot had 10,000 plants, the gross acreage in both cases is still 10 acres (4 hectares). However, the net acreage for the plot with 100 plants may be only 1 acre (0.4 hectares), while the net acreage for the plot with 10,000 plants may be 6 acres (2.4 hectares). The ratio of net acres to gross acres multiplied by 100 provides an estimate of the percentage cover of the infestation.

The total gross acreage of yellow starthistle in California is now estimated at 14.3 million acres (5.8 million hectares), an increase of over 80% from 1985 (table 1). Monterey County had the highest reported gross acres of yellow starthistle in the state, at 1.65 million acres (668,000 hectares). This was followed by Siskiyou County with just over 1 million acres (405,000 hectares), Mendocino County with 1 million acres (405,000 hectares) and Fresno County with 925,000 acres (374,000 hectares). In addition, four of the six counties previously reporting no yellow starthistle reported some infestations in 2002; only Orange and Imperial counties still reported none in 2002.

Eight counties reported no change since 1985 in the number of gross acres infested with yellow starthistle, and six counties reported a decrease in infested acres. All other counties reported an increase in infested gross acreage. The largest increase was reported by Monterey County, which jumped from only 6,000 acres (2,430 hectares) in 1985 to 1.65 million acres (668,000 hectares) in 2002. The largest proportional increase was reported for Ventura County, which jumped from just 5 acres (2 hectares) in 1985 to 250,000 acres (101,000 hectares).

Per Maddox and Mayfield (1985), we grouped the county infestation acreages by region (table 2). Although our grouping boundaries were not identical to those used by Maddox and Mayfield, they are similar. The differences are due to our grouping of counties as a whole instead of partitioning the estimates according to drainage area. The exception was the reported acreage for Riverside and San Bernardino counties, which occurred entirely within the South Coast drainage area; consequently, estimates from these counties were combined with the South Coast counties.

Our 2002 survey showed that the Sacramento Valley continued to have the largest amount of yellow starthistle gross acreage, with over 5.8 million acres (2.3 million hectares). The San Joaquin Valley followed with just over 3 million acres (1.2 million hectares), then the North Coast drainage with 2.8 million acres (1.1 million hectares) and the Central Coast drainage with 2.3 million acres (0.9 million hectares). These four regions represent over 98% of the total yellow starthistle gross acreage statewide.

Comparing the proportional amounts of the total yellow starthistle infestation located within each region for 1985 and 2002 showed little change except for the Central Coast drainage, which increased from 4.5% to 16.2% of the total gross acreage, and the North Coast drainage, which decreased from 35.3% to 19.6% of the total gross acreage (table 2). Interestingly, the amount of canopy cover of yellow starthistle (as estimated by the ratio between net and gross acreages) was similar among regions (rang-

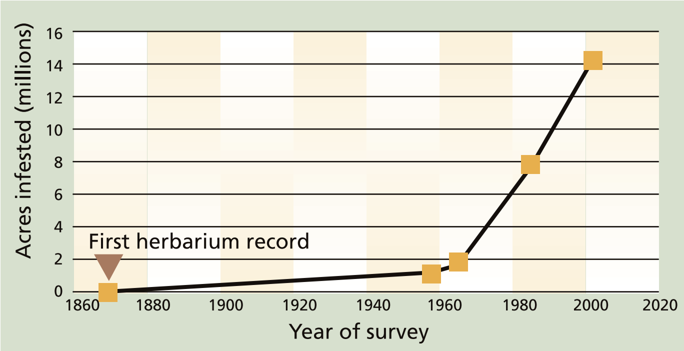

Fig. 3. Number of acres infested by yellow starthistle by year of survey. Sources: Maddox and Mayfield 1985, this report (2002).

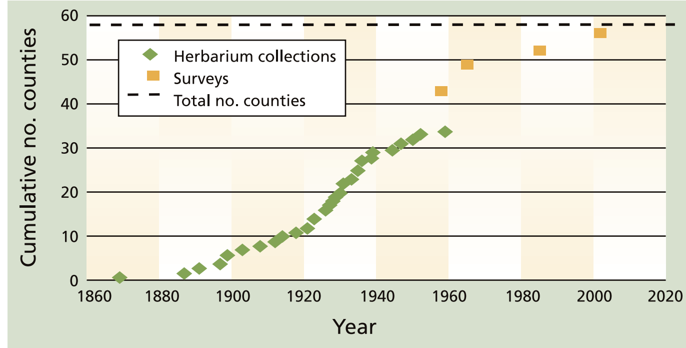

Fig. 4. Cumulative number of counties with yellow starthistle from 1869 through 2002. Data from the herbarium collections compiled by Doug Barbe, CDFA botanist (retired), for 1869 through 1960 (Calflora 2005). Survey data is from questionnaires from 1959 through 1985 (Maddox and Mayfield 1985) and this report (2002).

ing from 20% to 41%) except for the Central Coast drainage, which reported an estimated canopy cover of 6.5%. This suggests that, although the gross acreage was high, yellow starthistle cover was actually lower in the Central Coast drainage than elsewhere.

It must be emphasized that our estimates of yellow starthistle acreage are subjective and rely on the judgment of the county biologists. However, an acre-by-acre survey would be economically unfeasible. County biologists are trained to identify yellow starthistle and have good firsthand knowledge of the infestations in their county, so a subjective estimate may be our best estimate of infested acreage for an exotic weed that occurs over millions of acres.

Township levels vs. infested acres

The county survey of infested acres and the abundance of yellow starthistle by township were performed separately. However, we expected that the results of the two surveys were correlated, so to quantify this we summed the amount of acres identified as low or high in the township survey and compared the totals for each county with their estimate of infested acres. There was a significant correlation between the two data sets ($r = 0.61$, $P < 0.05$) when we assumed that the high-abundance townships were 45% infested with yellow starthistle (10,400 out of 23,040 acres [4,211 out of 9,328 hectares]) and the low-abundance townships were 17% infested (4,000 out of 23,040 acres [1,619 out of 9,328 hectares]). This suggests that the township abundance survey and the infested acres survey both yielded similar patterns of high and low abundance for yellow starthistle.

History of starthistle's spread

The invasion of California by yellow starthistle shows two phases of spread: a long initial period of slower spread prior to 1960 and a period of rapid spread after 1960 (fig. 3). An initial lag phase has been observed for other exotic weeds and is thought to be due to the weed's genetic adjustment to the new environment and the initiation of enough new founder populations to promote rapid spread (Weber 1998). Some insight into the early invasion dynamics of yellow starthistle may be obtained from the examination of early herbarium records. Doug Barbe, CDFA botanist (retired), visited the main herbaria throughout California and compiled a list of the locations and years of collection for yellow starthistle specimens collected through 1959. A total of 58 localities were obtained and the data were posted on the Internet by Fred Hrusa, the current CDFA botanist (Calflora 2005).

We used these records to examine the patterns of first yellow starthistle occurrence by county and the expansion of the weed's range throughout California (fig. 4). In addition to the herbarium data, we included the numbers of counties reporting infestations in the four surveys between 1959 and 2002. The data shows a logistic curve with the highest rate of increase between 1920 and 1940. There was a decline in new county collections after 1940, when yellow starthistle was no longer considered unusual. Once a species is widely recognized as a common weed, the collection of herbarium specimens often declines. However, the addition of the data from the county surveys after 1958 suggests a steady increase in spread from 1920 through 1965.

It appears that during the lag phase of the invasion, yellow starthistle gradually increased in abundance until around 1920, when the rate of spread increased. The earliest herbarium collections occurred within the Sacramento River and North Coast drainage areas (Calflora 2005), but beginning in the 1920s yellow starthistle was collected for the first time in San Bernardino and Santa Barbara counties in Southern California. This was a significant expansion of range.

Gerlach (1997) suggested that invasion of California by yellow starthistle occurred in a multiple-step process. Prior to 1900, yellow starthistle was likely introduced as a contaminant of alfalfa seed brought from Chile. The original source of alfalfa in Chile was Spain, so the yellow starthistle that was initially introduced to California may have been of Spanish origin. After 1900, California received contaminated alfalfa seed directly from several locations throughout Europe and Asia, including Spain, Italy, France, Turkey and "Turkestan" (an area consisting of parts of Turkmenistan, Uzbekistan and Kazakhstan) (Gerlach 1997). This suggests that different biotypes of yellow starthistle may have been introduced during this period.

Individual introductions of a species are only a sample of the genetic diversity of the original source popula-

Baldo Villegas/CDFA

Prior to 1960, yellow starthistle's rate of spread through California was about 13,500 acres annually; between 1965 and 2002 the rate escalated to more than 334,000 acres annually. *Above*, tall yellow starthistle plants in a pasture near Quincy.

Fig. 5. Historical distribution of yellow starthistle in California, 1941. Source: Robbins et al. 1941.

tion, and the lack of genetic diversity may limit a weed's ability to adjust and overcome biotic and abiotic barriers to establishment in its new habitat. The occurrence of multiple introductions and the subsequent hybridization of plants from formerly separated source populations may provide the necessary genetic material to allow a species to become successful in its new environment (Ellstrand and Schierenbeck 2000). The occurrence of multiple introductions of yellow starthistle into California suggests that local hybridization was possible, but its role in the invasion biology of this weed has not been examined.

Gerlach (1997) suggested that a second invasion began in the 1930s or 1940s, when yellow starthistle became associated with the grazing system being developed for the foothill grasslands. This second invasion was facilitated by changes in cropping practices from 1920 to 1940. Prior to 1920, early reports of yellow starthistle were associated with the irrigated alfalfa fields and dry-land crops (wheat and barley) located near the Sacramento River and its tributaries (Gerlach 1997). Later, with motorized vehicles becoming more common, the cropping systems and harvesting equipment began to move away from the watercourses.

Prior to the 20th century, agricultural production was concentrated near the Sacramento and San Joaquin rivers. Later, with the expansion of the state's irrigation system and the increased use of motorized vehicles, farming expanded away from the river system and into the foothills. The development of new roads into the foothills and the movement of large numbers of grazing animals between the valley and foothills provided an efficient method for yellow starthistle to spread into new areas.

The increase in rate of first occurrence by county (fig. 4) after 1920 is consistent with Gerlach's hypothesis. The movement of yellow starthistle into the foothill grazing system and assistance in its dispersal by the movement of infested agricultural products, animals and machinery, may have been the stimulus that allowed yellow starthistle to move into the second phase of its invasion statewide.

After 1960, the rate of spread of yellow starthistle increased dramatically. The slope of the linear regression of the amount of infested acres between 1965 and 2002 shows that the spread rate was 334,377 acres (135,400 hectares) per year (fig. 3). In contrast, prior to 1960 the rate of spread averaged only 13,500 acres (5,500 hectares) per year. A spread rate of 334,377 acres per year is quite high compared to other exotic invasive plants, as most are reported to spread at rates less than 250,000 acres (100,000 hectares) per year (Weber 1998; Smith et al. 1999). Moreover, since 1960 the rate of spread of yellow starthistle in California has been steady, almost linear, and there is no indication of it slowing down. Eventually, however, the rate of spread will decrease as maximum coverage is approached and more aggressive management programs are employed.

The expansion of yellow starthistle throughout California appears to have occurred in two ways: a steady diffusion away from existing population centers, and a disjunctive establishment of multiple satellite populations that were originally separated by great distances but eventually expanded and coalesced. Robbins et al. (1941) produced an early distribution map of yellow starthistle in California (fig. 5) that showed a high concentration of the weed within the Sacramento Valley; several small, scattered populations throughout the remainder of Northern California; and a few small populations in the San Joaquin Valley and the coastal counties of Southern California. This map, along with the early herbarium records, suggests that the initial population center for yellow starthistle was the Sacramento River drainage area. This area continues to have the highest number of infested acres today.

Baldo Villegas/CDFA

A statewide township survey conducted in 2002 identified more than 14 million gross acres infested with yellow starthistle, nearly double the level of a 1985 survey. *Above,* U.S. Department of Agriculture scientist Sharon Anderson collects leaf samples along an infested trail in Fresno County.

From 1985 to 2002, increases of infested acres occurred in all areas of the state except the Interior Great Basin and the desert regions. The increases in Southern California likely resulted from new founder populations as well as from the expansion of small existing populations, and these areas showed the highest proportional increases of this weed. However, yellow starthistle infestations in the Sacramento Valley continued to increase, indicating a filling in of the gaps in this area.

Future increases in abundance

Because this weed has a strong affinity for roadsides and can be transported on machinery and in feed and hay, it is likely that human activity accelerated the scattering of new founder populations and contributed to its high rate of spread. It is not certain how far east and southeast yellow starthistle will spread in the future because environmental factors that may limit its distribution (such as low annual rainfall) are not yet known. However, we anticipate yellow starthistle continuing to increase its density and distribution in both Northern and Southern California, with the highest rates of increase in the southern coastal counties.

Future increases in yellow starthistle abundance may be significant for land managers of areas not currently infested. To stop the spread, new infestations should be eradicated when populations are small and easy to control, taking into account biological control efforts already under way.

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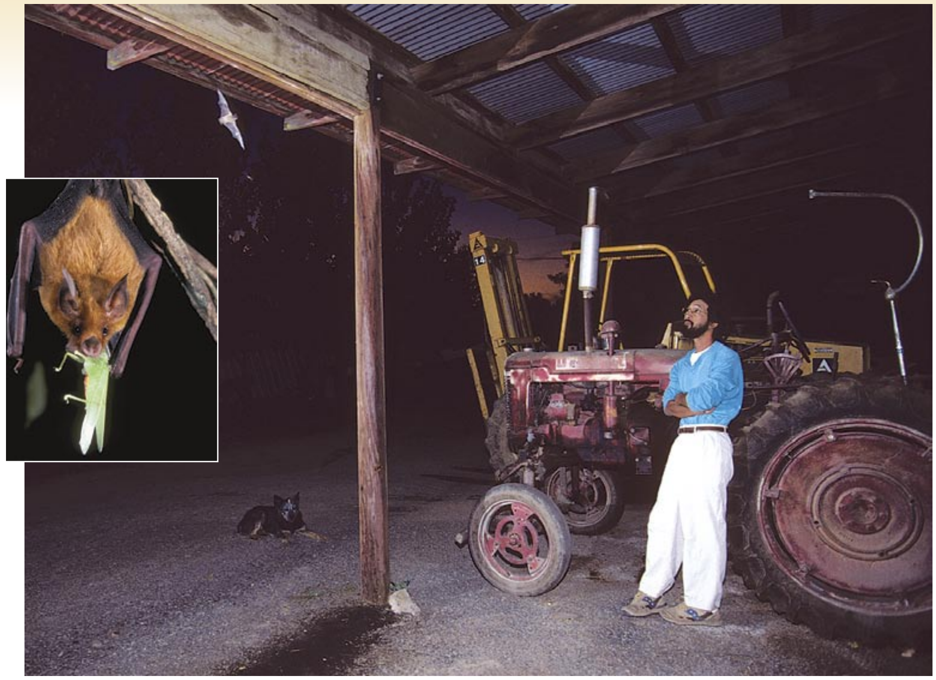
RESEARCH ARTICLE

Well-placed bat houses can attract bats to Central Valley farms

by Rachael F. Long, W. Mark Kiser
and Selena B. Kiser



Photos: Merlin D. Tuttle, Bat Conservation International

Although the role that insectivorous bats play in agricultural pest control is difficult to quantify, a colony of 150 can consume more than a million insects each year. The authors evaluated how to best attract bat colonies to Central Valley farms. *Above*, Cliff Fong, an organic grower in Yolo County, watches nocturnal bats in his barn. *Inset*, a bat eats an insect.

In an 8-year study from 1997 to 2004, we evaluated the use of 186 bat houses in rural areas of California's Central Valley. We considered the bat houses' size, color, height and location, and found that location was the main factor affecting bat use. Colonies of bats (generally mothers and their young) preferred houses mounted on structures such as buildings, shaded or exposed only to morning sun, and within one-quarter mile of water. In contrast, individual bats (generally males and nonreproductive females) were less selective in where they roosted. The overall occupancy rate for bat houses in our study was 48% for colonies and 28% for individual bats. Mexican free-tailed and Myotis bats were the main species using the houses, with occasional sightings of pallid and big brown bats. Bats occupied most houses within the first 2 years of placement.

California is home to 25 species of bats, seven of which are commonly found in the Central Valley: the Mexican free-tailed bat, big brown bat, pallid bat, California myotis, Yuma myotis, western red bat and hoary bat (table 1). Red and hoary bats tend to roost individually in trees, including orchards, whereas the others form maternity colonies (mothers and their young) in any suitable crevice such as buildings, bridges, trees or rocky outcroppings. Bat maternity colonies in California range in size from less than a hundred for big brown and pallid bats to thousands for Mexican free-tailed and Myotis spp. bats (Zeiner et al. 1990).

Most California bats are insectivorous, with the exception of two desert species in the extreme southern portion of the state that feed on nectar and pollen (Mexican long-tongued bat [*Choeronycteris mexicana*] and the lesser long-nosed bat [*Leptonycteris curasoae*]). Insectivorous bats feed on a variety of insects, but different species prefer different prey (Long et al. 1998). For example, big brown bats prefer beetles; hoary and red bats prefer moths; and pallid bats prefer crickets, beetles and scorpions (Whitaker 1995; Zeiner et al. 1990). Bats can consume their body weight or more in insects each night, and a typical colony of 150 bats can eat more than a million insects each year (Whitaker 1995). In the Central Valley, bats tend to hibernate or migrate to warmer areas during the winter when prey is scarce, and return each spring apparently to the same roost to raise their young (Zeiner et al. 1990).

Given the insect-eating nature of bats, farmers may have an interest in attracting them to their farms. Bat houses, akin to bird boxes but with the opening on the bottom, have been used to attract bats since the early 20th century (Campbell 1925; Tuttle et al. 2004). Although bats in many areas of the United States have successfully colonized bat houses, there is limited information on the parameters that make them suitable for use by bat colonies in California's Central Valley.

House design and placement

The purpose of our research was to evaluate the influence of the design and placement of bat houses on their use as roosting sites by bats in the Central Valley. From 1997 to 2004, 186 bat houses were installed and monitored yearly in 66 rural agricultural locations in California's Central Valley. The houses were constructed using guidelines provided by Bat Conservation International (Tuttle et al. 2004; BCI 2005). Houses were mostly made of plywood with one or more 3/4-inch- to 1-inch-wide chambers that were open at the bottom, allowing bats to fly in and out from below.

The houses were usually caulked and sealed to keep them dark and dry, and most had ventilation slots on the lower sides to prevent overheating. Wooden partitions inside the houses were either roughened or covered with plastic mesh to provide footholds for bats. The houses were categorized as small or

Left and center: Mark and Selena Kaiser, Bat Conservation International

Merlin D. Tuttle, Bat Conservation International

Far left, **Mark Kiser of Bat Conservation International installs a bat houses on a barn;** ***left,*** **houses installed on poles were less likely to attract bat colonies than those on barns;** ***top,*** **the inside of a bat house from below;** ***above*****, a colony of pallid bats.**

large (less than or greater than 3 linear feet of roost space as measured by the total length [side to side] of all roost chambers combined).

Internal temperature affects bat house occupancy, with females and young preferring houses between 80° F and 100° F (Tuttle et al. 2004). As a result, we mounted the bat houses in different locations to test the effect of shade or morning sun versus full day or afternoon sun on occupancy rates. Bat houses that received indirect heat through a wall to which they were attached were added to the appropriate category of sun exposure.

In some areas of the United States the color of bat houses influences their internal temperature, and darker houses are recommended for cooler regions and lighter colors for warmer areas (Tuttle et al. 2004). We tested whether color influenced the occupancy of bat houses in the Central Valley by painting them light, medium or dark colors; houses with no sun exposure were excluded from the data analyses.

To test the effect of mount height and type on bat house use, the houses were mounted individually, side-by-side or back-to-back on barns, sheds, poles, bridges or silos between 7 feet and 31 feet off the ground. All houses were at least 6 feet from surrounding objects, such as tree branches or wires, allowing the bats to easily maneuver in and out. In addition, all houses were within 2.5 miles of a permanent water source that was large enough for bats to drink from while on the wing, including canals, ponds and streams. However, because bats apparently favor roosts close to water, bat house occupancy was partitioned into less than and more than one-quarter mile from water (Tuttle et al. 2004).

The bat houses were inspected yearly (usually in June) with a flashlight, and the occurrence, number and species of bats using the houses were recorded. The two species of myotis look so similar that differentiating them would have required us to handle the bats, and we did not want to disturb the maternity colonies. Since bachelors (males and nonreproductive females) tend to roost individually and independently from mothers and their young, we separated our data by the number of bats using the houses. Houses with five or more bats were labeled as a colony (usually mothers and their young), whereas houses with less than five bats were labeled as individuals (usually males and nonreproductive females).

Data were analyzed using a chi-square distribution to test whether occupancy by both individual bats and colonies of bats depended on bat house height, color, size, mount type, distance to water, sun exposure and time since installation. The observed distributions of occupied bat houses were compared with the available distributions using chi-square contingency tables, and the power of the tests was calculated according to Cohen (1988).

Bat house occupancy

The overall occupancy rate for the bat houses was 76% (48% for colonies and 28% for individuals). Out of 141 occupied houses, Mexican free-tailed bats were found in 67% of the houses, myotis in 26%, pallid bats in 10% and big brown bats in 2%, with multiple species often sharing roosts (table 1). In 24% of the houses, the bats could not be identified due to blocked visibility. We suspect that the myotis were Yuma myotis, although California myotis could have been present but they have yet to be identified using bat houses. Colonies ranged from five to 500 bats per house, with an average size of 64 (± 10) bats.

The rate of initial occupancy by colonies of bats reached 64% in the first 2 years, but declined significantly to 27% for houses that had been up for more than 4 years without previous use ($P < 0.05$) (fig. 1A). In contrast, individual bats exhibited no significant differences in time until first occupancy ($P > 0.05$). For both individuals and colonies, there were no significant differences in the occupancy rates for small versus large

Bats can consume their body weight or more in insects each night, and a typical colony of 150 bats can eat more than a million insects each year.

TABLE 1. Characteristics of bats common to California's Central Valley

Bats common to the Central Valley	Prey preference	Bat house occupancy* by species (%)	Primary roosting behavior
Mexican free-tailed bat *(Tadarida brasiliensis)*	General insect predators†	67	Colony forming in buildings, trees, rocky crevices, caves, mines
California myotis *(Myotis californicus)* Yuma myotis *(M. yumanensis)*		26	
Pallid bat *(Antrozous pallidus)*	Beetles, crickets‡	10	
Big brown bat *(Eptesicus fuscus)*	Beetles	2	
Western red bat *(Lasiurus blossevillii)*	Moths	0	Mostly solitary in trees, including orchards
Hoary bat *(L. cinereus)*		0	

* Data from 141 houses that were occupied by one or more species of bats.
† Moths, flies, mosquitoes, leafhoppers, beetles.
‡ Also scorpions and centipedes.

houses, house color or house height ($P >$ 0.05) (table 2).

However, bat house occupancy rates were significantly influenced by their location (fig. 1B). Colonies were found more often in bat houses on structures than in those on poles (53% vs. 34% occupancy, respectively, $P < 0.05$). In contrast, individuals were found more often in bat houses on poles than in those on structures (40% vs. 23% occupancy, respectively, $P < 0.05$).

Bat colonies also favored bat houses with shade or morning sun versus those with full or afternoon sun (57% vs. 37% occupancy, respectively, $P < 0.05$) (fig. 1C). In contrast, individual bats were more often found using bat houses with full or afternoon sun versus those with shade or morning sun (39% vs. 19% occupancy, respectively, $P < 0.05$). Colonies also favored houses that were within one-quarter mile of a permanent water source over those located farther away (59% vs. 34% occupancy, respectively, $P < 0.05$), with no such differences observed for individual bats ($P >$ 0.05) (fig. 1D).

Location, location, location

The results of our study showed that several factors influence the attraction of bats to bat houses in California's Central Valley. Bat colonies favored bat houses mounted on structures such as barns or bridges, with shade or morning sun, and within one-quarter mile of water. In contrast, individual bats were more often found using bat houses on poles and in full or afternoon sun, while proximity to water was not important within the 2.5-mile area considered. The height, color and size of the bat houses had little impact on occupancy rates, especially for colonies. Although bat house size did not affect occupancy in our study, larger houses appear to offer bats more temperature gradients inside the houses and are preferred in other areas of the country (Kiser and Kiser 2004).

Bat colonies likely preferred bat houses attached to structures because these tended to be buffered from temperature fluctuations, which can exceed 30° F during the summer months in the Central Valley. This is important for bat pups, which are born helpless and without fur, to help them stay warm when their mothers leave the roosts at night to feed. Moreover, pole-mounted bat houses may have the disadvantage of increasing bat predation because they serve as perches for owls and hawks (author, personal observation).

Bat colonies probably preferred bat houses in the shade or morning sun because those with full or afternoon sun likely get too hot. Central Valley summer temperatures often exceed 100° F, and the optimum temperature for raising young bats is between 80° F and 100° F (Kiser and Kiser 2004). However, bats sometimes use south- or east-facing bat houses, particularly in the spring and fall when temperatures are cooler. As a result, it is probably best to place several houses around a farm to optimize roosting sites for bats.

Although there were no differences in occupancy rates as a function of bat house height, it is important to mount houses at least 10 feet off the ground to protect the bats from cats and other predators that can catch them if they fly too close to the ground (Tuttle et al. 2004). Likewise, bat houses should be mounted at least 20 feet from obstacles, such as wires or trees, that could block the entrance or serve as perches for predators including snakes, hawks and

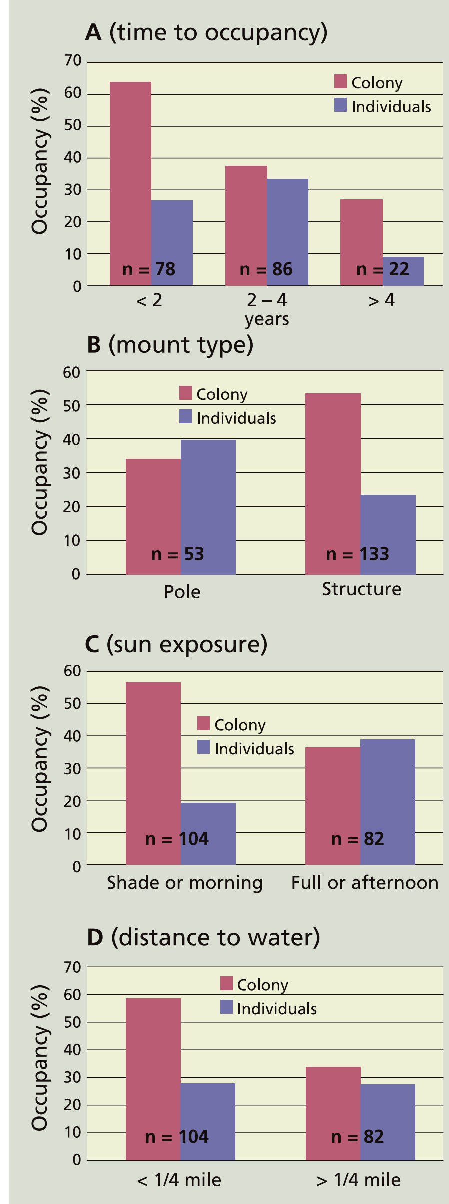


Fig. 1. Bat house occupancy by (A) time to first occupancy in years (from time of installation), (B) mount type, (C) sun exposure and (D) distance to water, by colonies (generally mothers and their young with ≥ five bats per house) and individuals (generally males and nonreproductive females with < five bats per house). (A) Colonies were more likely to occupy the houses within the first 2 years of placement (x^2 = 15.1, 2 df, $P < 0.05$, $\alpha >$ 99%) with no such differences observed for individual bats (x^2 = 5.4, 2 df, NS, α = 99%). (B) Colonies preferred houses mounted on structures (barns, silos, bridges) to those on poles (x^2 = 5.7, 1 df, $P < 0.05$, α = ca. 99%); individuals were more often found in houses on poles (x^2 = 5.0, 1 df, $P < 0.05$, α = 80%). (C) Colonies preferred houses with shade or morning sun (x^2 = 7.5, 1 df, $P < 0.05$, $\alpha >$ 99%); individuals more often used houses with full day or afternoon sun (x^2 = 8.9, 1 df, $P < 0.05$, α > 99%). (D) Colonies preferred houses within one-quarter mile of water (streams, canals, ponds) (x^2 = 11.0, 1 df, $P < 0.05$, $\alpha >$ 99%), with no such differences observed for individuals (x^2 = 0.001, 1 df, NS, α = 44%).

TABLE 2. Occupancy of bat houses by bat colonies and individuals based on height, color and size

Parameter	Number occupied	Total number	Chi-square distribution*, x^2	Power at $\alpha = 0.05$
Colonies†				
Height (feet)				
7–10	6	19	$x^2 = 2.5$, 3 df, NS	> 99%
11–15	45	91		
16–20	28	54		
21–31	10	22		
Color‡				
Light	22	60	$x^2 = 2.8$, 2 df, NS	ca. 87%
Medium	6	19		
Dark	25	50		
Size§				
Small	10	23	$x^2 = 0.2$, 1 df, NS	ca. 99%
Large	79	163		
Individuals¶				
Height (feet)				
7–10	4	19	$x^2 = 1.3$, 3 df, NS	> 95%
11–15	26	91		
16–20	14	54		
21–31	8	22		
Color‡				
Light	24	60	$x^2 = 4.3$, 2 df, NS	ca. 87%
Medium	4	19		
Dark	12	50		
Size§				
Small	8	23	$x^2 = 0.6$, 1df, NS	33%
Large	44	163		

* Nonsignificant (NS) values for bat house height, color and size show a lack of preference by bats for differences within these categories.

† Bat houses with ≥ five bats per house were categorized as a colony (generally mothers and their young).

‡ Based on visual rating of color intensity; houses with no sun exposure were excluded from the data analyses.

§ Small versus large: less than or greater than 3 linear feet of roost space (total length, side to side, of all roost chambers combined).

¶ Bat houses with < five bats per house were categorized as individuals (generally males and nonreproductive females).

Photos: Merlin D. Tuttle, Bat Conservation International

Bats found in California include: *top to bottom*, hoary bat, Mexican free-tailed bat and red bat.

owls. Bat houses should also be placed within a quarter mile from a permanent water source, such a canal, pond or stream; this was favored by bat colonies in our study area as well as elsewhere in the country (Tuttle et al. 2004).

When bat colonies occupied the bat houses in our study, they either showed up as a group, which may have been due to the loss of a roost site, or they started off with a few individuals and slowly increased in numbers. Bat houses were most likely to be occupied by colonies within the first 2 years of placement. Our data suggests that bats either like the houses and move in, or do not and will probably never use them. If houses are not used after 2 to 4 years, our data suggests that they should be moved to new locations.

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Rabies prevention

Although bat rabies is rare in California, it is usually fatal. Bat houses should be placed in areas with minimal human disturbance, because young or sick bats will occasionally fall out of roosts where they may come in contact with people or pets. When putting up a bat house, remind people to leave the bats and bat house alone. If someone handles a bat without gloves or is bitten by a bat, they should seek medical attention immediately. Vaccinating cats and dogs and never touching a bat can almost always prevent rabies (Wilson 1997).

New crop coefficients developed for high-yield processing tomatoes

by Blaine R. Hanson *and* Donald M. May

Processing tomato yields have increased by 53% over the past 35 years, but the current seasonal crop-evapotranspiration requirements that growers use to schedule irrigation are based on 1970s-era data. We updated this data and developed new crop coefficients for processing tomatoes using the Bowen ratio energy balance method in eight commercial fields from 2001 to 2004. Today's evapotranspiration rates are similar to those of the early 1970s, indicating a substantial increase in water-use efficiency by processing tomatoes during the past 35 years. In addition, we collected data in both furrow- and drip-irrigated fields, but no statistical differences were found between them.

Thanks to site-specific breeding, processing tomato yields in California have increased by more than 50% since the early 1970s, while water-use efficiency has increased about 40%. Bowen ratio instruments were used to collect climate and soil data from processing tomatoes, in order to calculate evapotranspiration and update crop coefficients.

California produces nearly 95% of the processing tomatoes grown in the United States (CTGA 2005; USDA 2005). Nearly one-third of the state's tomato acreage is in the Central Valley's Westlands Water District (2005). Statewide, the average yields of processing tomatoes have increased by more than half (53%) from the early 1970s to the early 2000s (from 23.7 tons per acre for 1970 to 1974, to 36.3 tons per acre for 2000 to 2004), with most of the yield increase occurring after 1975 (CTGA 2005).

This long-term yield increase is the result of breeding programs that developed new tomato varieties better adapted to the climate and soil conditions of the Central Valley. In addition to higher yields, these new varieties also have better fruit quality. Furrow irrigation is commonly used in processing tomato cultivation, although drip irrigation is increasing, particularly in salt-affected soils along the west side of the San Joaquin Valley. Recent studies have shown that tomato yields in these salt-affected soils are considerably higher for drip irrigation compared to sprinkler and furrow irrigation (Hanson and May 2003).

Managing tomato irrigation water efficiently requires estimating crop evapotranspiration (ET_c) — its water use — between irrigations. ET_c is commonly estimated by multiplying a crop coefficient by a reference crop evapotranspiration (ET_o). ET_o is the evapotranspiration of well-watered grass and is obtained from the California Irrigation Management Information System (CIMIS), operated by the California Department of Water Resources. The crop coefficient is the ratio of ET_c to ET_o, and depends on crop type and growth stage. During the 1970s, the seasonal ET_c for processing tomatoes in the Central Valley ranged from 25.1 to 28.1 inches, depending on planting time, with an average seasonal value of 25.4 inches (Fereres and Puech 1981).

Crop coefficients vary with crop type and stage of growth. There are four growth stages: (1) initial, from planting to about 10% canopy coverage, including planting, germination and stand establishment; (2) crop development, from about 10% to about 75% canopy coverage; (3) midseason, 75% coverage to the start of maturity, encompassing bloom, fruit-set and the majority of fruit sizing; and (4) late season, from full maturity to harvest or complete senescence. Midseason crop coefficients (during the period of the highest ET_c) were developed from previous experimental data and range from 1.05 under subsurface drip irrigation (Phene et al. 1985) to 1.25 under sprinkler irrigation (Pruitt et al. 1972). More recently, the recommended midseason coefficients were 1.10 to 1.15 (Allen et al. 1998), although the source of these coefficients was not identified.

Several studies have shown a linear relationship between tomato yield and ET_c. The long-term processing-tomato yield increase since 1975, coupled with the variability in crop coefficients determined from experimental data conducted 20 to 35 years ago, raise questions about current ET_c requirements. This study evaluated the water usage of processing tomatoes on the west side of the San Joaquin Valley in furrow- and drip-irrigated commercial fields under a wide range of cultural practices used by growers, in order to develop more up-to-date evapotranspiration data and new crop coefficients.

Assessing evapotranspiration

From 2001 to 2004, we determined the ET_c for processing tomatoes using three furrow-irrigated and five drip-irrigated commercial fields near Five

TABLE 1. Characteristics of eight sites used in processing tomato study

	2001		2002		2003		2004	
	Furrow	Drip	Furrow	Drip	Drip (H2003)	Drip (D2003)	Furrow	Drip
Planting date	April 16	April 18	April 8	April 2	March 1	May 1	April 25	May 25
Bed spacing (in.)	66	66	60	60	60	66	66	66
Planting type*	T	T	D	D	D	T	T	T
Establishment†	S	Dr	S	S	S	Dr	S	S
Rows/bed	1	1	1	1	2	1	1	1
Crop season (days)	121	128	133	147	138	109	125	133
Variety	BOS 3155 Heinz 9557	Heinz 9557 Heinz 9665 Heinz 9773	Heinz 9491	Heinz 9773 Peto-Hypeel 303	SUN 6117	Heinz 9557 Peto-Hypeel 303	Heinz 9780	Heinz 9492 Heinz 9665

* T = transplants; D = direct-seeded.
† S = sprinkler; Dr = drip.

Points, about 50 miles southwest of Fresno. Measurements were made in one drip-irrigated field and one furrow-irrigated field each year except for 2003, when measurements were made in two drip-irrigated fields. At all sites, irrigation water-management decisions were made by the growers or consultants hired by the grower. The soil type was clay loam for all fields.

The eight commercial fields that we studied were selected to represent a wide range of cultural practices (table 1). One plant row per bed was used at all sites except one (H2003), a drip-irrigated field with two plant rows per bed. Furrows ranged from about 640 to 800 feet long, and alternate furrow irrigation was used throughout except during the canopy development stage in 2001.

Drip lines were installed from 8 to 14 inches deep, and their lengths were 2,600 feet in 2001, and 1,200 feet during the rest of the study. Emitter spacing was 12 inches from 2001 through 2003, and 18 inches in 2004. In 2002, the subsurface drip system was replaced at the end of June due to emitter clogging; the new lines were installed in every other furrow. At all sites, each bed contained one drip line per bed, except for the surface drip system.

ET_c was determined with the Bowen ratio energy balance (BREB) method using Campbell Scientific (Logan, Utah) systems. The BREB method calculates ET_c from measurements of net radiation, soil heat flux, soil temperature, soil water content, wind speed, air temperature and dew point temperature. A computer ET model developed by Hsiao and Henderson (1985) was used to estimate ET_c during the cultivation periods, which required the removal of the BREB systems, and during periods of instrument problems. There was a difference of 5% or less between the cumulative ET_c estimated by the model (calibrated from the BREB data) and the BREB systems.

Using experimental plots in commercial fields sacrifices the statistical rigor of a randomized replicated design. However, there are several important advantages to using commercial fields: (1) ET_c is determined under the conditions experienced by growers, (2) ET_c reflects the fieldwide conditions, and (3) fields can be selected to reflect a range of cultural practices used by tomato growers.

Moreover, there are several reasons why it is not practical to measure ET_c in a randomized, replicated experimental design. Plot sizes must be relatively large because the BREB method requires a significant amount of fetch, or area of crop around the instruments. A fetch-to-instrument height above the surface of 100-to-1 is commonly used as a rule of thumb. For example, at maximum canopy coverage in our study, the instruments were positioned 6.5 feet above the ground surface and so required 650 feet of fetch. Furthermore, instruments would be needed in each plot, which — at $15,000 to $20,000 per setup — would be prohibitively expensive.

Crop coefficients were calculated as the ratio of ET_c to ET_o. The latter was obtained from the California Irrigation Management Information System (CIMIS) station at the UC Westside Research and Extension Center, about 3 to 5 miles from the eight study fields.

Crop evapotranspiration trends

Initially, the 2001 furrow ET_c was 0.22 inches per day due to sprinkler-irrigated stand establishment, but rapidly decreased to nearly 0.05 inches per day for the next 25 days (fig. 1A). Thereafter, ET_c increased during canopy development, reaching maximum values on or about day 170, and then decreasing again to the season's end. During canopy development, ET_c spikes occurred due to furrow irrigations, which wet the soil surface across the bed. The 2001 drip ET_c was very small at the beginning of the crop season due to stand establishment with the drip system, but increased with time to maximum values of nearly 0.3 inches per day. Thereafter, drip ET_c generally fluctuated between 0.22 and 0.32 inches per day. The average midseason ET_c was 0.29 inches per day for furrow and 0.27 inches per day for drip irrigation.

In 2002, both furrow and drip ET_c values exceeded 0.17 inches per day due to sprinkler irrigation at the beginning of the crop season, but ET_c rapidly decreased to less than 0.08 inches per day followed by relatively constant values until the start of canopy development (fig. 1B). ET_c then rapidly increased to high midseason values of 0.31 inches per day for both irrigation methods. Drip ET_c decreased near the end of the crop season, indicating a late-season growth stage; no similar behavior occurred for the furrow ET_c.

Relatively high initial values of ET_c occurred for H2003 (drip irrigation) due to sprinkler irrigation, followed by values generally smaller than 0.05 inches per day for about 35 days (fig. 1C). The initial values for D2003 (drip irrigation) were about 0.05 inches per day due to the drip-irrigated stand establishment, followed by a rapid increase in ET_c after about 23 days. Average midseason values were 0.27 and 0.31 inches per day for D2003 and H2003, respectively.

In 2004, two sprinkler irrigations occurred for both furrow and drip irrigation during initial growth. Following the second sprinkler irrigation of the furrow site, ET_c decreased slightly but then increased to maximum values at midseason (fig. 1D). After day 210, furrow ET_c decreased with time. Drip ET_c increased with time after the second sprinkler irrigation, reaching midseason values on about day 220. After day 220, drip ET_c generally decreased with time. Average midseason values were 0.30 and 0.27 inches per day for furrow and drip irrigation, respectively.

TABLE 2. Average daily midseason crop coefficients and statistical analysis for processing tomato

	2001		2002		2003		2004	
	Furrow	Drip	Furrow	Drip	Drip (H2003)	Drip (D2003)	Furrow	Drip
Sample size	24	37	29	37	47	30	45	37
Average	1.02ab*	0.96b	1.06c	1.05ac	1.05c	0.99ab	1.09d	1.08d
SD	0.04	0.05	0.04	0.06	0.04	0.11	0.04	0.02
CV (%)	3.73	4.74	4.12	6.25	3.95	11.38	4.25	2.13
Minimum	0.92	0.84	0.96	0.92	0.96	0.72	0.93	1.02
Maximum	1.11	1.07	1.13	1.30	1.15	1.19	1.16	1.14

*Values with the same letter were statistically similar at a level of significance of 0.05, based on the t-test.

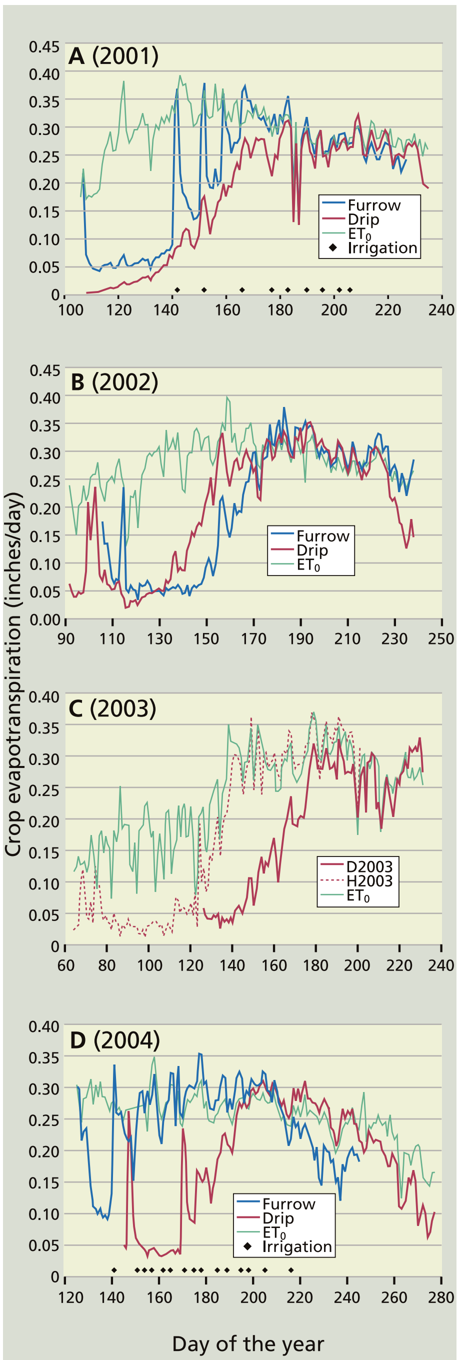

Fig. 1. Daily reference crop evapotranspiration and daily crop evapotranspiration for furrow and drip sites in (A) 2001, (B) 2002, (C) 2003 (drip only) and (D) 2004.

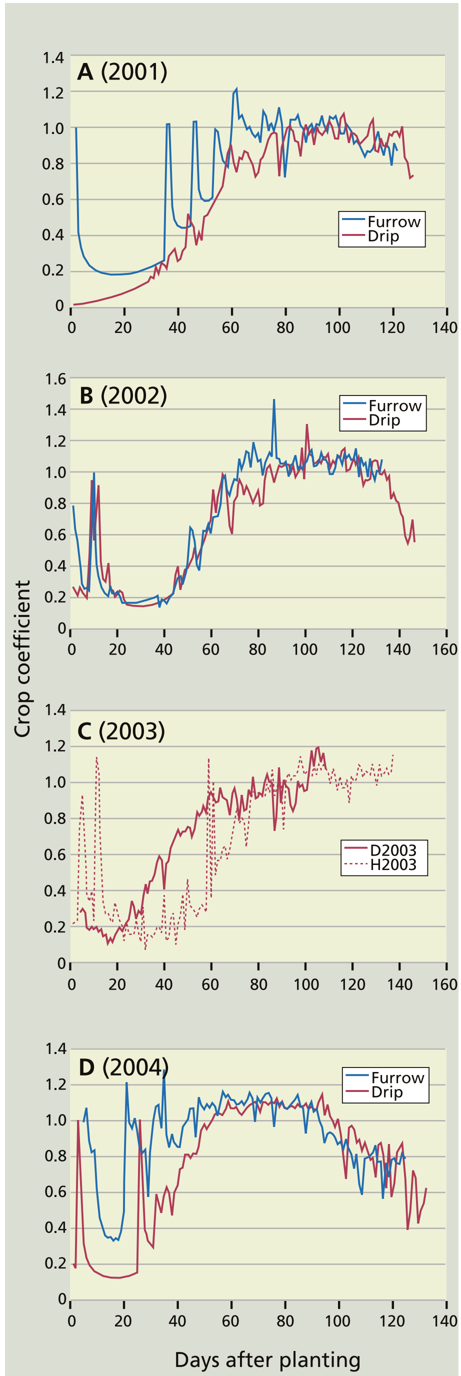

Fig. 2. Daily crop coefficients with days after planting for (A) 2001, (B) 2002, (C) 2003 and (D) 2004.

Daily crop coefficients

During sprinkler irrigation at the start of the crop season, crop coefficients were nearly equal to 1 for all years; this indicates that ET_c was nearly equal to ET_0 during sprinkler irrigation because of evaporation from the soil surface (fig. 2). Maximum crop coefficients determined from the BREB data ranged from 0.91 to 1.21, with an average of 1.03. The average crop coefficient between sprinkler irrigation and 10% canopy coverage was 0.19, due to a substantial reduction in evaporation caused by a drying soil surface. Crop coefficients at the start of the crop season were smaller than 0.3 for sites where subsurface drip irrigation was used for stand establishment. During canopy development, crop coefficients increased rapidly to values generally exceeding 1.

The crop coefficients remained relatively constant during midseason, but the average midseason crop coefficient varied year to year from 0.96 to 1.09 (table 2). No statistical differences were found between the midseason crop coefficients of the two irrigation methods in any year. The 2001 coefficients were smaller and generally statistically different from those of the other years, while the 2004 coefficients were higher and statistically different from those of the other years. These average midseason coefficients were similar to those found by Phene et al. (1985), but smaller than those of Pruitt et al. (1972).

The daily crop coefficient data showed well-defined late-season growth stages for only the 2002 drip system and the 2004 drip and furrow systems. The average crop coefficients for the last 5 days of the measurement period were 0.55 (2004 drip), 0.59 (2002 drip) and 0.78 (2004 furrow). No late-season stages of decreasing ET_c were found for the other sites.

Canopy growth rates

Canopy coverage over time (days after planting) showed similar growth rates for drip- and furrow-irrigated fields in 2001 and 2002, due to similar planting dates and types (figs. 3A and B). A slight decrease in canopy coverage occurred near the end of the crop season due to vine training (pushing the vines in the furrow back onto the bed) and/or trimming (cutting off vines in

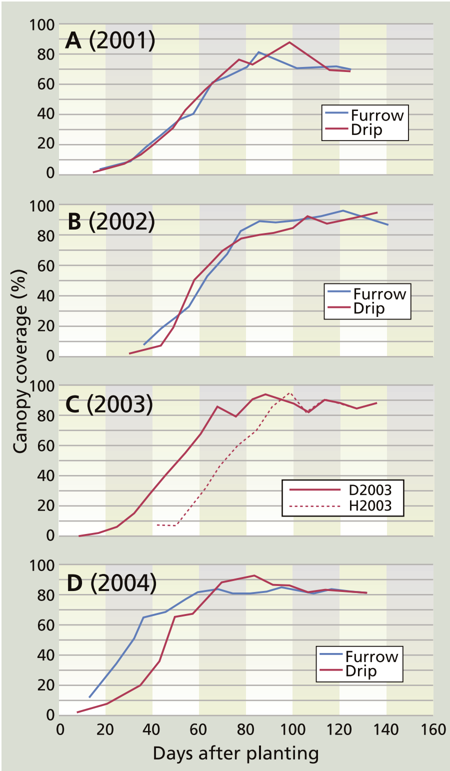

Fig. 3. Canopy coverage (%) versus days after planting for (A) 2001, (B) 2002, (C) 2003 or (D) 2004.

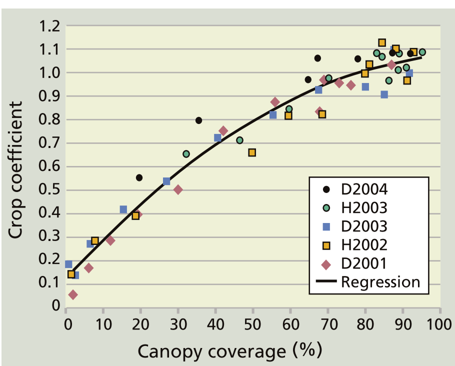

Fig. 4. Relationship between average crop coefficient and canopy coverage.

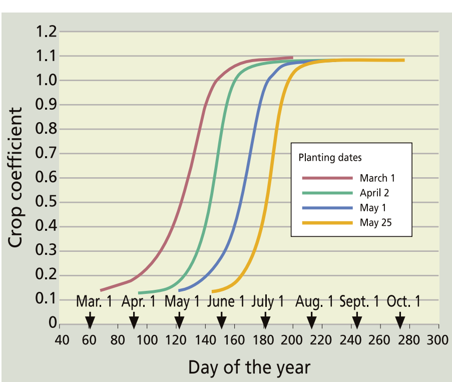

Fig. 5. Family of curves showing crop coefficients versus time of year for planting times of March 1, April 2, May 1 and May 25.

the furrow), methods used to improve air circulation and reduce mold and rot in the canopy.

The canopy growth of H2003 (drip irrigation) lagged behind that of D2003 (drip irrigation) because the former was planted much earlier (March 1 vs. May 1, respectively) (fig. 3C). This early planting date resulted in a much longer initial growth stage. However, similar values of maximum canopy coverage occurred in both 2003 fields.

In 2004, growth rates varied between the two fields due to different planting dates and stand establishment problems with the drip-irrigated field (fig. 3D). These problems slowed down the initial growth rate of the drip-irrigated field, but eventually its canopy coverage recovered to nearly 90%. The canopy coverage of the drip field later decreased to about 80% due to vine training.

Coverage and crop coefficients

We described the relationship between canopy coverage (C) and crop coefficient (K_c) using a second-order polynomial equation (fig. 4). Crop coefficients that occurred during the sprinkler irrigations or were calculated by the computer model were excluded from this relationship. A regression analysis developed the following equation:

$$K_c = 0.126 + (0.0172)(C) - (0.0000776)(C^2). \quad (1)$$

The regression was highly significant, with a coefficient of determination of 0.96. This relationship appeared to be independent of specific field characteristics.

Equation 1 can be used to determine crop coefficients from canopy coverage data for Central Valley processing tomatoes. However, this may be inconvenient due to the time required to measure canopy coverage. Therefore, based on the canopy growth curves for different planting times and equation 1, we developed a family of curves showing crop coefficients by time of year for various planting times (fig. 5). Some adjustments may be needed for site-specific conditions. For example, the canopy growth of transplants may be 10 to 20 days ahead compared to direct-seeded plants for similar planting times.

Soil water tension

The soil water tension data (not shown) indicated that most of the time, the irrigation frequencies and amounts of irrigation water applied during this study were adequate, and that ET_c rates and processing tomato yields should not be adversely affected by water stress. The exception was H2002 (drip irrigation), where clogging of the drip lines during the initial and canopy-development growth stages caused soil water tensions to exceed 200 centibars (maximum values less than 80 centibars are recommended). Interestingly, the canopy growth rate and processing tomato yield for that field did not show any adverse effects due to these high tensions.

Water-use study results

Evapotranspiration. For all years, seasonal crop ET_c ranged from 20.8 to 29.6 inches (table 3), and the average difference in ET_c between irrigation methods was not statistically significant (*t*-test, level of significance = 0.05). The average ET_c of all sites was 25.5 inches with a standard deviation (SD) of 3.1 inches. The average ET_c of the furrow systems was 27.4 inches (SD = 2.0 inches) and the drip systems was 24.4 inches (SD = 3.1 inches).

Applied water. Applied water ranged from 22.9 to 40.1 inches. The furrow irrigation amounts included surface runoff that was recovered and reused elsewhere on the farms. The D2003 high water applications reflected an attempt by the irrigator to reverse decreasing soil water potential at the 6-inch depth. Reasons for the high water application of H2003 (drip irrigation) were not clear.

Yields. Crop yields ranged from 35.1 to 65.5 tons per acre. The large yield of H2003 reflected its very early planting time, which experience has shown results in larger yields. Differences between average yields of furrow and drip irrigation were not statistically significant, which is not surprising considering the variability in the data. There was no correlation between crop yields and ET_c; we believe the main reason for this was the different processing-tomato varieties planted, based on a separate study that we conducted on the effects of variety on yield under drip irrigation (May and Hanson 2004). Year-to-year climate variability and different crop seasons also may have contributed to the crop yield differences.

TABLE 3. Water-use efficiency (WUE), seasonal evapotranspiration (ET_c), seasonal applied water and tomato yield of eight study sites

2001	Furrow	Drip
Seasonal ET_c (in.)	25.5	22.5
Applied water (in.)	32.9	22.9
Yield (ton/acre)	38.5	41.8
Soluble solids (%)	5.6	5.1
WUE (ton/acre/in.)	1.51	1.86
2002	**Furrow**	**Drip**
Seasonal ET_c (in.)	27.1	29.2
Applied water (in.)	26.0	30.1
Yield (ton/acre)	35.1	39.2
Soluble solids (%)	*	*
WUE (ton/acre/in.)	1.29	1.34
2003	**Furrow (H2003)**	**Drip (D2003)**
Seasonal ET_c (in.)	24.5	20.8
Applied water (in.)	31.6	35.2
Yield (ton/acre)	65.5	40.7
Soluble solids (%)	4.7	5.6
WUE (ton/acre/in.)	2.67	1.96
2004	**Furrow**	**Drip**
Seasonal ET_c (in.)	29.6	24.8
Applied water (in.)	40.1	24.6
Yield (ton/acre)	52.0	36.2
Soluble solids (%)	5.2	*
WUE (ton/acre/in.)	1.76	1.45

* Data not available.

Water-use efficiency. Water-use efficiency, defined as the ratio of yield to ET_c, ranged from 1.29 tons (2002 furrow) to 2.67 tons (H2003) per acre per inch. The average water-use efficiency was 1.52 and 1.86 tons per acre per inch for furrow and drip irrigation, respectively, but these values were not statistically different (*t*-test, level of significance = 0.05).

It has been hypothesized that the seasonal ET_c of subsurface drip irrigation may be smaller than that of furrow irrigation due to reduced evaporation from the soil. The only previous study found on this matter showed little difference in seasonal ET_c — measured with lysimeters — between surface drip and furrow irrigation of processing tomatoes (Pruitt et al. 1984).

The only conclusion that can be drawn from our current study is that evaporation under subsurface drip irrigation may be smaller during the early growth stage compared to furrow irrigation, as shown by the furrow and drip ET_c data for 2001. For the furrow system, relatively high ET_c due to evaporation from the wet soil surface occurred during the stand-establishment sprinkler irrigation and during furrow irrigations at the canopy development stage, as evidenced by the spikes in the ET_c data (fig. 1). During those irrigations, wetting of the soil surface occurred across the bed width. In contrast, little wetting occurred with the subsurface drip system. Cumulative ET_c at the end of canopy development was 4.6 inches higher for the furrow system as compared to the subsurface drip system. Similar behavior, however, was not found for the 2002 and 2004 furrow systems. These systems were managed so that soil-surface wetting was minimal, reducing the evaporation component of ET_c during canopy development.

Seasonal trends. In 2002, the seasonal ET_c for drip irrigation was 2.1 inches more than that for furrow irrigation. Contributing factors were the longer crop season of the drip system as well as reduced evaporation during furrow irrigation at the early growth stages due to limited surface wetting during furrow irrigation. The 2004 data showed higher seasonal furrow ET_c when compared to seasonal drip ET_c. However, this difference was partly due to different planting times and problems with the stand establishment in the drip system.

Efficient irrigation scheduling

The seasonal ET_cs that we calculated are similar to those reported by Fereres and Puich in 1981. Therefore, the 53% increase in processing tomato yields since the mid-1970s has not increased the seasonal ET_c. Instead, the average water-use efficiency of processing tomatoes has increased by about 50% during the same period (from 0.93 to 1.42 tons per acre per inch). For the same amount of water per acre, much higher tomato yields are being obtained today compared to those of 35 years ago.

It is unlikely that converting from furrow to drip irrigation in processing tomatoes will reduce seasonal ET_c. While some reduction in water use may occur during the early growth stages, as shown by the 2001 data, the 2002 and 2004 data showed that evaporation under furrow irrigation can be reduced. Stand establishment with subsurface drip irrigation may reduce ET_c during the initial growth stage compared to sprinkler irrigation, but this approach is feasible only for transplanted fields. There is little or no opportunity for reduced drip ET_c during midseason because for a given year, similar midseason crop coefficients occurred with both irrigation methods.

To provide sufficient water to meet crop ET_c requirements, we recommend that processing tomato growers schedule irrigations using either the relationship between canopy coverage and coefficients along with ET_o data, or the family of curves in figure 5.

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Fall foliar sprays prevent boron-deficiency symptoms in grapes

by L. Peter Christensen, Robert H. Beede *and* William L. Peacock

Foliar spraying was found to be an effective method to rapidly increase boron levels in most vegetative and reproductive tissues in grapevines. The reduction of fruit-set deficiency symptoms with a pre-bloom or bloom spray was immediate but not complete. Foliar sprays applied during the previous fall were more effective in reducing such symptoms than pre-bloom or bloom sprays. This may be due to the earlier incorporation of boron in reproductive tissues, especially dormant buds. Grapevine foliage is also more tolerant to boron postharvest in the fall, when 1 pound per acre of actual boron can be safely applied. Spring and summer sprays of boron should be limited to 1/2 pound per acre per application to avoid phytotoxicity.

A boron-deficient Thompson Seedless cluster in the trial vineyard shows reduced fruit-set, the presence of numerous pumpkin-shaped "shot berries" and necrosis of some branching. Fewer than 10% of the berries are normal size and shape.

After zinc, boron is the second most-important micronutrient deficiency problem in California vineyards. Boron deficiencies are most common in the old flood plains and alluvial fans of the Stanislaus, Merced, San Joaquin, Kings and Kaweah rivers; the Sierra Nevada foothills; and North Coast sites with basaltic soils subject to high rainfall. Vineyard boron deficiencies are mostly associated with soils derived from basaltic and granitic parent material of the Sierra Nevada and North Coast ranges. Low boron is also associated with higher rainfall areas and soils irrigated with snowmelt water originating from the Sierra Nevada. In contrast, boron levels are typically higher and can even be toxic in soils originating from marine sedimentary material, such as in the Central Coast range.

Grapevine reproductive tissues are most sensitive to boron deficiency, which results in reduced fruit-set, small "shot berries" that are round to pumpkin-shaped, and flower and fruit cluster necrosis. Boron deficiency can have a drastic effect on fruit quality and yield, even when there are only mild-to-moderate foliar symptoms. At the same time, the over-application of boron can result in plant phytotoxicity. Phytotoxicity begins as a necrosis of the leaf margins that can cause a downward cupping of the young leaves. The necrosis intensifies and becomes more general as boron accumulates in older leaves.

Most commonly, grape growers have applied boron to the soil by hand or as a direct soil spray, sometimes in combination with an herbicide application (Christensen 1986; Christensen and Peacock 2000). However, such applications must be carefully timed to allow for winter rainfall or irrigation to move the boron into the root zone. Boron applications by foliar spray and drip irrigation are of increased interest for their convenience and the potential for faster vine response.

Foliar boron application has been studied in tree crops such as pears, prunes, cherries and almonds, and the application timing was found to influence fruit-set and development (Batjer and Thompson 1949; Callan et al. 1978; Hanson 1991b; Nyomora and Brown 1999). However, there is limited research on vine uptake and response to foliar boron and the potential for toxicity. We conducted several studies on the timing of boron foliar-spray applications in an eastern Fresno County vineyard with mild-to-moderate boron deficiency symptoms.

Foliar sprays increase uptake

The studies were conducted in 1998 and 1999 in an own-rooted, furrow-irrigated 'Thompson Seedless' grape vineyard on Delhi loamy sand. The vineyard was irrigated with canal water and about 25% supplementation from well water. The extremely low boron content of canal water can contribute to low boron availability in sandy vineyard soils.

A preliminary study was conducted in 1998 to determine the influence of foliar sprays on boron concentrations in vegetative and reproductive parts of the vine at bloom. Spray treatment was applied at 2 1/2 weeks pre-bloom on May 6, 1998. The two comparative treat-

Boron foliar sprays applied in the fall were the most effective treatment to prevent, *above*, boron deficiency symptoms in grapes.

ments were an untreated control and a foliar boron spray at 1 pound per acre applied as Solubor (20.5% boron) at 100 gallons per acre (gpa). The trial design was a randomized complete block with four-vine plots, replicated 10 times. Vine tissue samples were taken at bloom on May 23, 1998; triple-rinsed with distilled water and oven-dried; and analyzed for boron at the ANR Analytical Laboratory at UC Davis.

The comparative tissues were 30 opposite cluster petioles, 30 2-inch shoot tips and 15 flower clusters per plot. The flower clusters were separated into the cluster stem framework (rachis) and the individual unopened flowers (inflorescences). While the trial area was of low boron status, the presence of boron-deficiency symptoms in fruit was not extensive enough to compare the treatments for visual evaluation or yield response.

Boron levels were significantly increased by the spray treatment in all of the sampled tissues (table 1), including tissues receiving the direct spray (petioles, rachis and inflorescence), as well as the new shoot-tip growth that was not yet present at the time of spraying. Care was taken to sample only actively growing shoot tips that had grown beyond the spray deposit. Representative shoot tips were marked with a black felt pen at the time of treatment, in order to measure subsequent new growth. Therefore, boron would have been translocated into the growing shoot tip from the sprayed tissues below. These results suggested that there is some phloem mobility of boron, and that foliar sprays have the potential to prevent boron deficiency of shoots in a timely manner during the growing season. (Phloem is the inner bark of a shoot that primarily conducts organic compounds.)

Spray timing and type

A follow-up study was conducted in the same vineyard during 1999, in an area observed in 1998 to be severely boron deficient. We compared the effects of boron timing and spray type (foliar vs. soil) on fruit-set and development as well as on vine tissue concentrations. There were five treatments: (1) control (untreated); (2) fall foliar, Oct. 19, 1998; (3) dormant soil berm spray, Feb. 8, 1999; (4) pre-bloom foliar, May 4, 1999; and (5) bloom foliar (50% calyptrae [caps] off), May 20, 1999.

All treatments were applied at 1-pound boron per acre as 20.5% boron soluble product. The foliar sprays were applied at 150 gallons per acre, and the berm soil spray was applied at 30 gallons per acre (10 gallons per vineyard acre in a 4-foot-wide band along the vine row). The trial design was five-vine plots, replicated five times in a randomized block design.

Treatment effects on vine-tissue boron concentrations were determined with laboratory analysis. The following samples were collected: dormant canes (cane and bud tissues) in treatments 1 and 2 to determine boron uptake from the fall foliar spray, Feb. 26, 1998; early bloom (opposite cluster petioles, 2-inch shoot tips and entire flower clusters), May 17, 1999, in all treatments; and veraison (2-inch shoot tips), July 15, 1999, in all treatments.

Thirty samples of each tissue type were collected from each plot. The cane samples consisted of one-node sections (each cut at mid-internode). The buds were excised and analyzed separately. All tissue samples were triple-rinsed in distilled water, oven-dried and analyzed for boron at the ANR Analytical Laboratory at UC Davis.

Fruit response was determined by visually grading all individual clusters in each plot for the presence of boron deficiency symptoms on Aug. 15, 1999. Each cluster was scored as the percentage of the cluster showing combined symptoms of reduced fruit-set and the presence of the pumpkin-shaped shot berries characteristic of boron deficiency.

All of the data was subjected to ANOVA. When treatment effects were significant ($P \leq 0.05$), treatment means were separated by Duncan's new multiple range test.

Tissue boron increases

The fall foliar treatment significantly increased boron levels in the dormant bud tissues, but the cane tissues were not affected (table 2). At bloom, the pre-bloom foliar treatment had the highest boron concentrations of all sampled tissues. The fall foliar treatment also increased bloom tissue boron levels, but not as much as the pre-bloom foliar treatment. The bloom treatment had not yet been sprayed at the time of tissue sampling and so was similar to the control. The dormant soil treatment did

TABLE 1. Effect of a pre-bloom boron (B) foliar spray on Thompson Seedless tissue boron levels at bloom, Kingsburg, Fresno County, 1998

Treatment	Petioles	Rachis*	Inflorescences†	Shoot tips
	ppm dry wt			
Control, no B	24.6b‡	19.2b	19.6b	26.4b
B foliar spray	85.2a	103.4a	202.2a	243.0a

* Flower cluster stem structure only.
† Flower tissue only.
‡ Means followed by a different letter within columns are significantly different according to Duncan's new multiple range test, $P \leq 0.05$.

TABLE 2. Effect of boron soil and foliar spray treatment on Thompson Seedless tissue boron levels from dormancy to veraison, Kingsburg, Fresno County, 1999

	Dormancy (Jan. 26)		Bloom (May 17)			Veraison (July 15)
Treatment	Canes	Buds	Petioles	Infl.*	Shoot tips	Shoot tips
	ppm dry wt.					
Control, no B	10.6a†	20.2b	25.5c	14.8c	25.8c	27.6b
Fall, foliar	10.0a	27.6a	32.3b	22.0b	32.8b	36.0a
Dormant, soil	—	—	26.8bc	16.0bc	28.2abc	31.4ab
Pre-bloom, foliar	—	—	90.2a	113.2a	78.4a	35.6a
Bloom, foliar	—	—	24.8c	14.6c	28.8bc	36.6a

* Inflorescences.

† Means followed by a different letter within columns are significantly different according to Duncan's new multiple range test, $P \leq 0.05$.

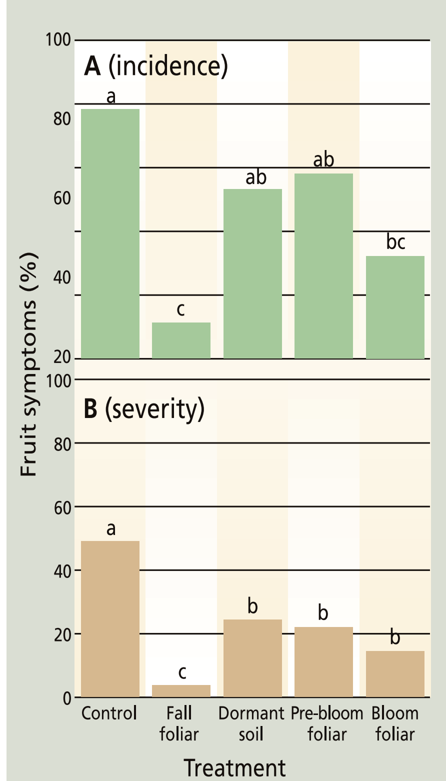

Fig. 1. Effects of boron soil and foliar spray treatment on (A) incidence (mean % clusters showing > 5% symptom expression) and (B) severity (mean % of fruit showing deficiency in all clusters) in a Thompson Seedless grape vineyard, Kingsburg, 1999. Treatment means with different letters are significantly different according to Duncan's new multiple range test, $P \leq 0.05$.

not increase boron in the sampled tissues by bloom. At veraison, all of the foliar spray treatments (fall, pre-bloom and bloom) increased shoot-tip boron levels. The dormant soil treatment was intermediate among the treatments in shoot-tip boron concentration and was not different from either the control or the three foliar treatments. This 1999 study confirmed the 1998 pre-bloom spray treatment results by showing that boron concentrations increased in all of the sprayed tissues, as well as in new shoot tips thereafter.

Foliar boron spraying can be used as a temporary or emergency treatment, or as a method of vineyard maintenance.

Evidence of phytotoxicity after treatment was noted with the pre-bloom and bloom foliar sprays, but not with the fall foliar or the dormant soil berm sprays. Young, expanding leaves showed some necrosis and cupping at their margins. This demonstrated that spring and summer spray treatments should be used at a lower rate than the 1 pound of boron per acre used in our trial; one-half pound of boron per acre spray treatments have been shown to be safe at these times.

Fall sprays best for fruit

Boron deficiency in fruit was reported as incidence (clusters in which 5% or more of the fruit had symptoms) and severity (mean percentage of deficiency symptoms appearing in all of the clusters). The incidence of boron deficiency in the control was 78% (fig. 1A). Likewise, the fall foliar treatment had the lowest severity of boron-deficiency symptoms in fruit (3%) (fig. 1B). The other boron treatments (dormant soil, pre-bloom foliar and bloom foliar) also reduced fruit symptom severity, but not as effectively as the fall foliar treatment.

Vine fruit response did not correspond directly with tissue boron levels. While fruit symptoms were reduced more effectively by the fall foliar than the pre-bloom foliar treatment, tissue boron levels were higher in the latter than in the former treatment. This may be due to the inability of the pre-bloom foliar spray to reverse some earlier effects of boron deficiency on primordial tissue in developing buds. Also, at pre-bloom, the calyptrae (caps) prevent the foliar spray from contacting the unexposed flower parts (anthers, stigma, style and ovaries). These calyptrae are shed at bloom, along with their spray deposits, finally exposing the flower parts to complete their pollination and fruit-set.

Boron mobility

Boron has long been recognized as being immobile or only slightly mobile in the phloem of many plant species (Brown et al. 2002). However, boron is highly mobile in the phloem of certain plants, including pome fruits, stone fruits and nut tree crops of *Malus*, *Prunus* and *Pyrus* spp., respectively (Brown and Hu 1998a, 1998b; Hanson 1991a). This boron mobility is due to the production of sugar alcohols, enabling the cotransport of boron-polyol complexes in the phloem (Brown et al. 1999). Such plants accumulate boron in their apical tissues and exhibit boron toxicity as shoot-tip dieback.

Tree crops that have responded well to foliar boron sprays at pre-bloom, bloom and/or fall include almonds (Nyomora et al. 2000), cherries (Hanson 1991b), pears (Batjer and Thompson 1949) and prunes (Callan et al. 1978). All of these trees have been demonstrated to be phloem-mobile for boron. Fall foliar boron sprays have sometimes shown superior improvements in both fruit-set and yields in prunes and almonds as compared to spring sprays (Callan et al. 1978; Nyomora and Brown 1999).

The mobility of boron in grapevine tissues is not well understood. Scott and Schrader (1947) found that boron concentrations in mature grape leaves declined when boron was absent from the root environment, suggesting remobilization of boron from leaves. Remobilization of boron is its movement from one organ to supply another organ or tissue in the plant. Brown and Hu (1998b) found native, wild grapevines *(Vitis californica)* to be intermediate in phloem boron mobility when compared to other woody plants. Nonmobile plants always accumulate boron in the edges of older leaves (Brown and Hu 1998a), a characteristic of the European grape *Vitis vinifera* (Christensen and Ayers 1974). Also, Jennifer M. Hashim

Boron deficiencies are common in the old flood plains and alluvial fans of California's Central Valley. *Above,* a newly planted table grape vineyard.

grapevines are susceptible to temporary boron deficiency of developing tissues during periods of drought, suggesting limited boron mobility.

Therefore, *Vitis* spp. do not appear to show the same characteristics of boron mobility and accumulation as the phloem-mobile tree crops of *Malus*, *Prunus* and *Pyrus* spp. In this study, some limitations in phloem boron mobility of grapevines may explain our finding that the pre-bloom boron spray was less effective at reducing fruit symptoms than the fall spray. Pre-bloom-applied boron may not have been sufficiently translocated into the flower parts by bloom to prevent some fruit symptom development. Conversely, fall-applied boron may have been incorporated into floral parts early enough to prevent most deficiency effects at bloom. The bloom spray tended to be intermediate between the pre-bloom and fall sprays in fruit response. At bloom, the calyptrae are shed, exposing the floral parts, including pollen, to a direct foliar spray. This direct contact with boron may have enhanced fruit-set as compared to the pre-bloom spray.

Spray timing and rates

Our results indicate that fall foliar treatment may be the best insurance against boron-deficient inflorescence tissues at bloom. While pre-bloom and bloom foliar treatments can also reduce boron-deficiency symptoms in fruit, growers should consider an earlier treatment in the fall because it may be more effective. Foliar spraying can also be used to correct vegetative boron-deficiency symptoms, as indicated by increased boron concentrations in shoot tips after spraying. The soil treatment in this study was only partially effective in correcting the boron deficiency. However, only 1 pound of actual boron was applied per acre, whereas 4 to 5 pounds boron per acre are normally recommended as an initial soil treatment under furrow irrigation. The 1-pound rate was used in all treatments in this trial to make a direct comparison of treatment method only.

Foliar boron spraying can be used as a temporary or emergency treatment, or as a method of vineyard maintenance. With annual treatment, there should ultimately be enough residual boron in the soil to provide for more constant uptake and long-term correction of the deficiency. Spring and summer applications of boron should not exceed 0.5 pound per acre for each spray to avoid phytotoxicity. Mild necrosis at the margins of immature leaves can occur at rates exceeding 0.6 to 0.8 pounds boron per acre. The annual recommended rate of 1-pound boron per acre can be safely achieved by applying two sprays of 0.5 pound each. However, vine foliage is more tolerant of boron after harvest in the fall, safely receiving up to 1 pound per acre in a single application.

Most soluble boron products are derived from sodium borates, resulting in well-buffered, alkaline solutions of pH 8.6 to 8.7. If the boron is to be combined with a product that is susceptible to alkaline hydrolysis, then it will be necessary to reduce the pH with an acidifier such as citric acid. (Always follow label directions.)

After initial foliar spray treatment, growers may wish to switch to another method of boron application for maintenance, such as fertigation with drip irrigation (Peacock and Christensen 2005). The choice of application method can be based on equipment availability and convenience while using the same fertilizer product. Growers should also routinely monitor boron treatments with leaf petiole or blade analysis, due to the narrow margin between boron deficiency and toxicity.

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SIX DECADES OF . . . California AGRICULTURE

60 years ago | 50 years ago | 40 years ago | 30 years ago

Editor's note: In honor of our 60th anniversary, *California Agriculture* is publishing excerpts from past issues. Fifty years ago, *California Agriculture* was a black-and-white, monthly, 16-page magazine featuring short reports on a variety of agricultural and natural resource matters; a two-page color spread appeared in June 1956 to help growers identify plants damaged by air pollution.

Plant Damage by Air Pollution: Visible injury to plants by atmospheric pollutants amounts to millions of dollars in some affected areas

Production and quality of an important number of field, flower, fruit, ornamental and vegetable crops — in many of the important growing areas of California — are adversely affected by air pollution. Visible injury to 11 crops in the Los Angeles area has caused losses exceeding $3,000,000 annually since 1953. Development of protective measures and abatement programs is essential for some relief from losses due to air pollution. The air-borne toxicants responsible for most of the crop damage are ethylene, fluorides, herbicides, oxidized hydrocarbons, ozone and sulfur dioxide, and can be identified by plant response.

— John T. Middleton, A.S. Crafts, R.F. Brewer, and O.C. Taylor, (June 1956)

Enemies of Spotted Alfalfa Aphid: Lady beetles, hover flies, lacewings are the important native predators of aphids and other economic pests of alfalfa

Natural enemies — native insect predators and fungus diseases — helped to hold the spotted alfalfa aphid in check during the 1955 season. Although predators do not always prevent economic outbreaks of the spotted alfalfa aphid, they are important in holding down light infestations and preventing reinfestation after a chemical control treatment has been applied. The importance of predators varies from field to field, area to area, and season to season. It is the entire complex of predators working together that is significant in holding the aphids in check.

— Ray F. Smith and Kenneth S. Hagen (April 1956)

Headlines from 1956:

"2,4-D Damage to Young Citrus: Young lemon, orange, and grapefruit trees may be severely damaged by direct application of, or by the drift of 2,4-D"
— E.C. Calavan, T.A. DeWolfe, and L.J. Klotz (April 1956)

Removal of Tinter in Ponderosa: Prescribed burning of forest brush during the wet season by tested methods effectively reduces hazard of wildfire
— H.H. Biswell and A.M. Schultz (February 1956)

Household Buyers Choose Beef: Interviewees in Berkeley survey give reasons for selection between U.S. Good and U.S. Choice steak and sirloin
— Jessie V. Coles (May 1956)

Machine Harvesting of Grapes: Annual labor requirements stabilized by shifting part of the harvest work to growing season when labor needs slacken
— A.J. Winkler and Lloyd H. Lamouria (May 1956)

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